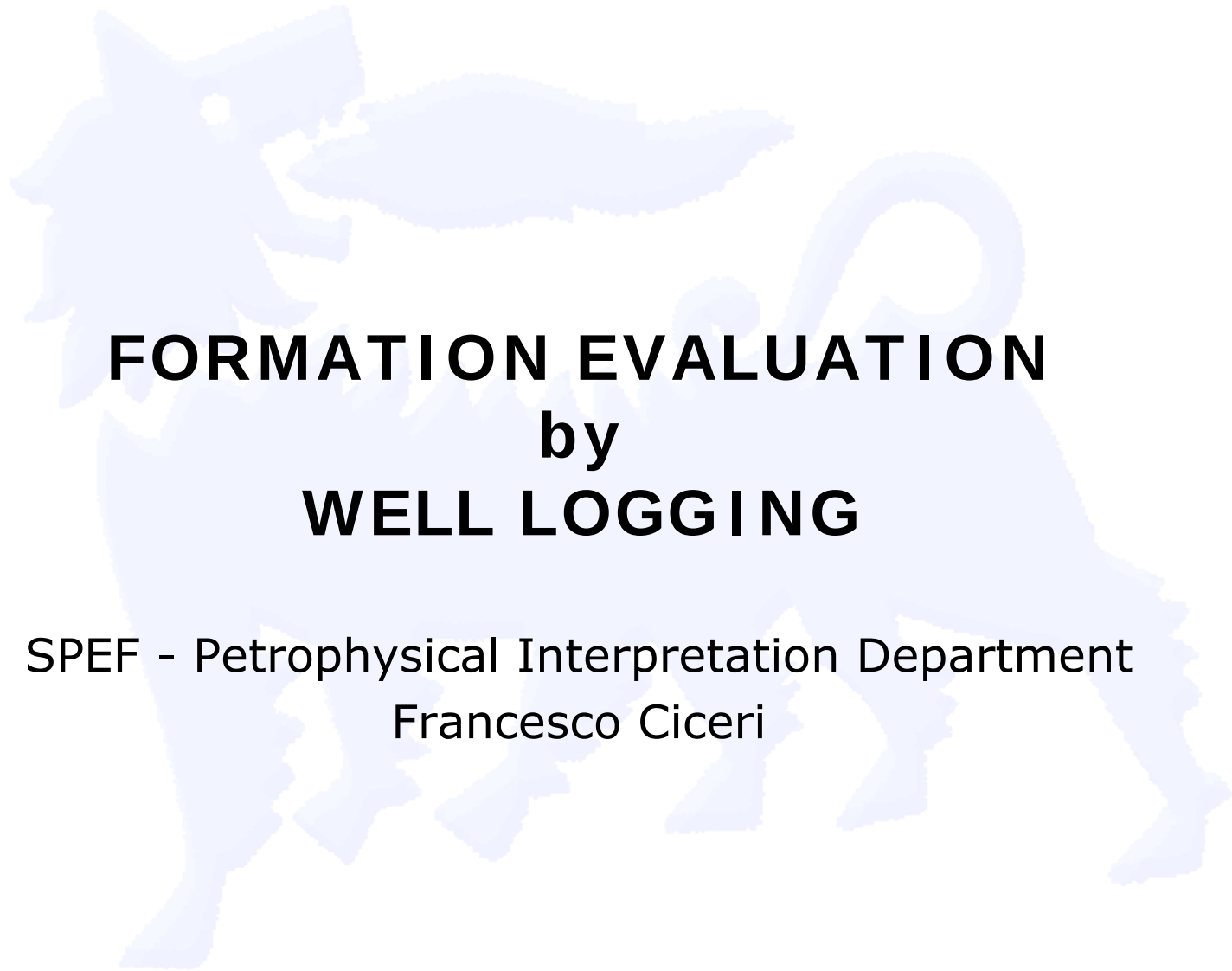


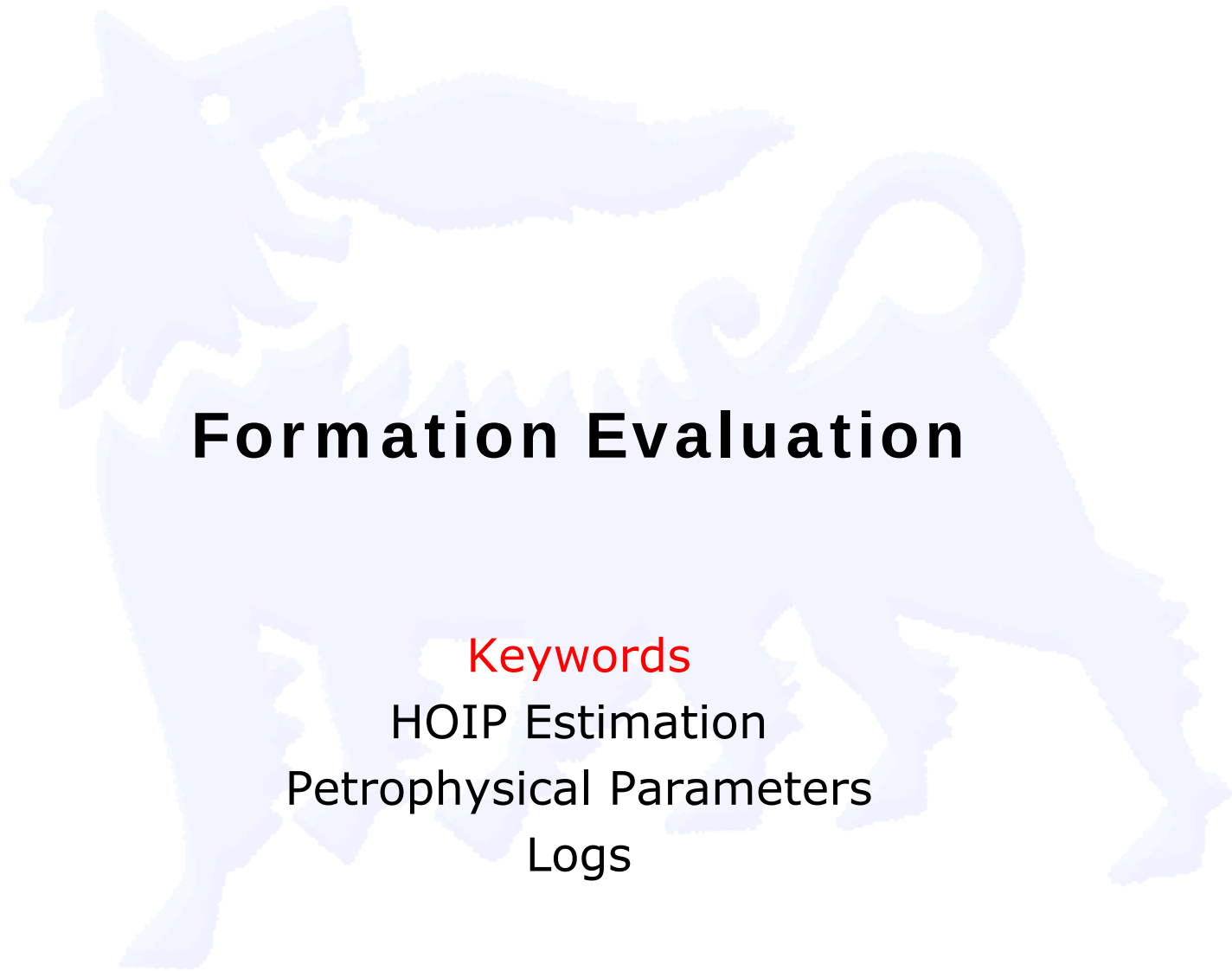


FORMATION EVALUATION by WELL LOGGING

SPEF - Petrophysical Interpretation Department
Francesco Ciceri

Agenda

- Formation Evaluation
- Well Logs
- Integrated Petrophysical Interpretation ?



Formation Evaluation

Keywords

HOIP Estimation

Petrophysical Parameters

Logs

Formation Evaluation Goal

- Objective of **Formation Evaluation** is to determine:
 - the dimension of the reservoir
 - **the quantity of hydrocarbon originally in place (HOIP)**
 - the productivity of the reservoir
- **Formation Evaluation** is the process of evaluating the petrophysical characteristics of a reservoir, making use of measurements and data from the well

Formation Evaluation Measurements & Interpretation

- The available data and measurements are usually of different nature:
 - Surface Logs (Mud logging)
 - Cores / Plugs
 - **Electrical Logs**
 - Production tests
- The analysis of these data and measurements is called **Integrated Petrophysical Interpretation**

Electrical Logs Analysis

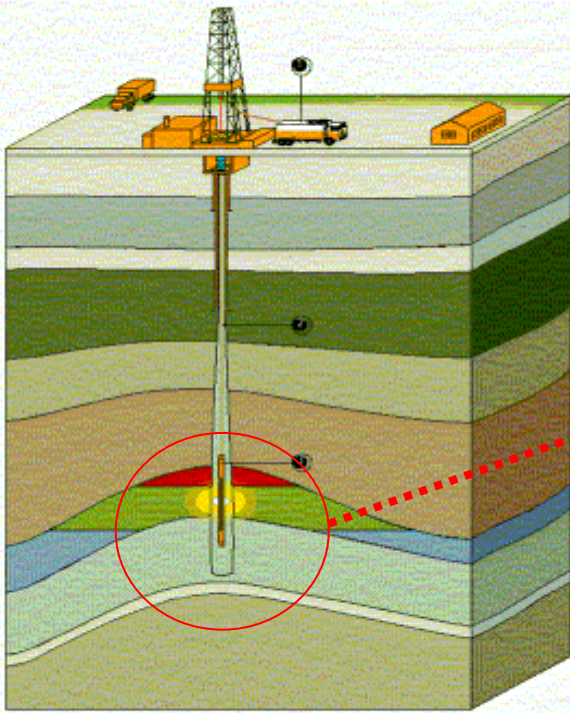
- **Geophysical (or Electrical) Logs** are used to derive the geological and petrophysical parameters of a formation from the measurement of physical parameters taken inside a well
- Therefore, Electrical Logs Analysis is an **indirect method** to estimate the main petrophysical parameters
- Electrical Logs (also called “Well Logs”) are recorded and analysed in all Hydrocarbon Exploration and Production phases:
 - during the drilling phase
 - after the drilling phase
 - during the productive life of the well

Well Logs

- **Well Logs** are the measurements of physical properties of the formation;
 - Resistivity
 - Density/Porosity
 - Hydrogen index
 - Natural radioactivity
 - Temperature
 - Acoustic properties
 -
- These measurements are used to estimate the petrophysical parameters of the formation through a process called **Petrophysical Interpretation**

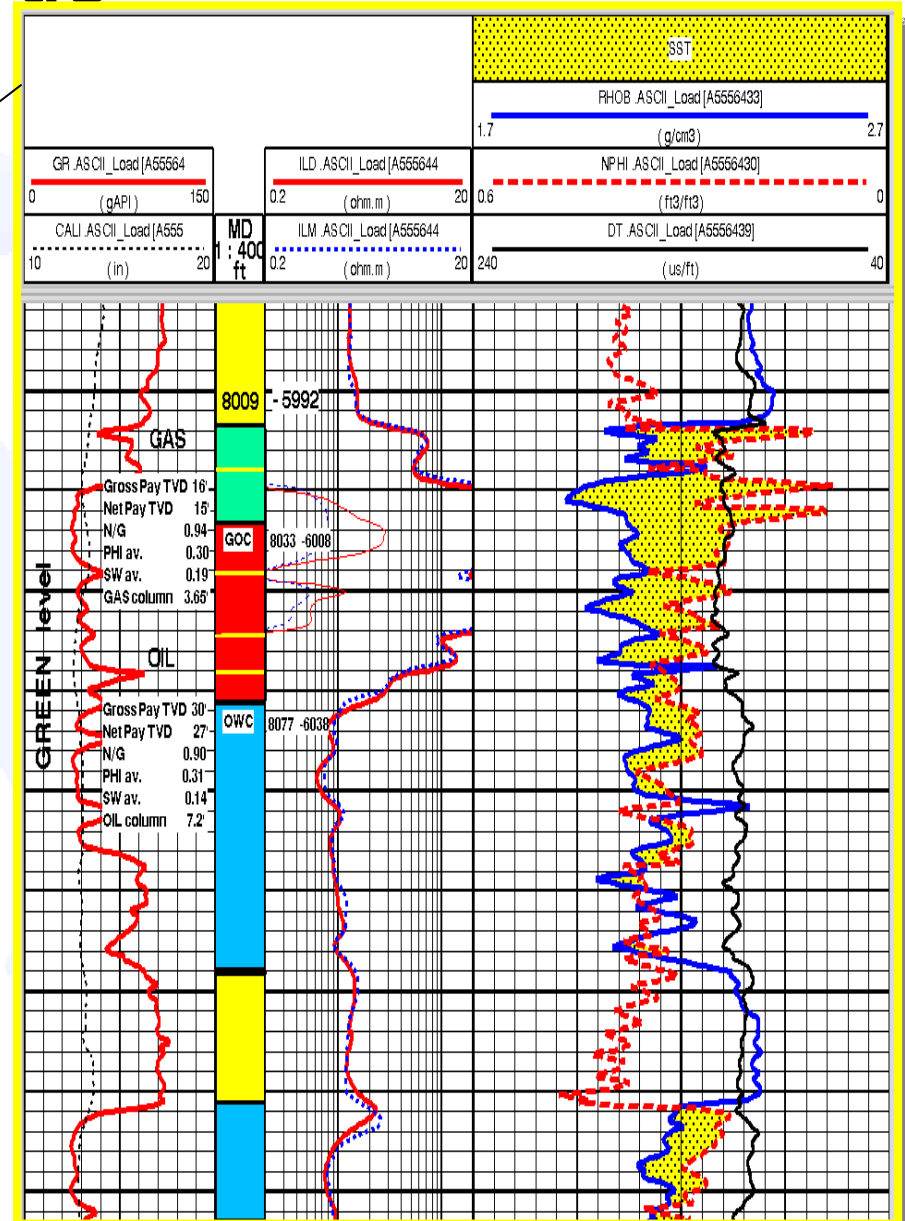
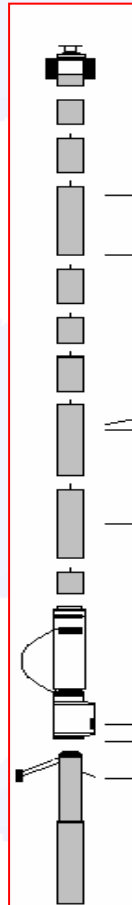
Well Logs

Logging the Well



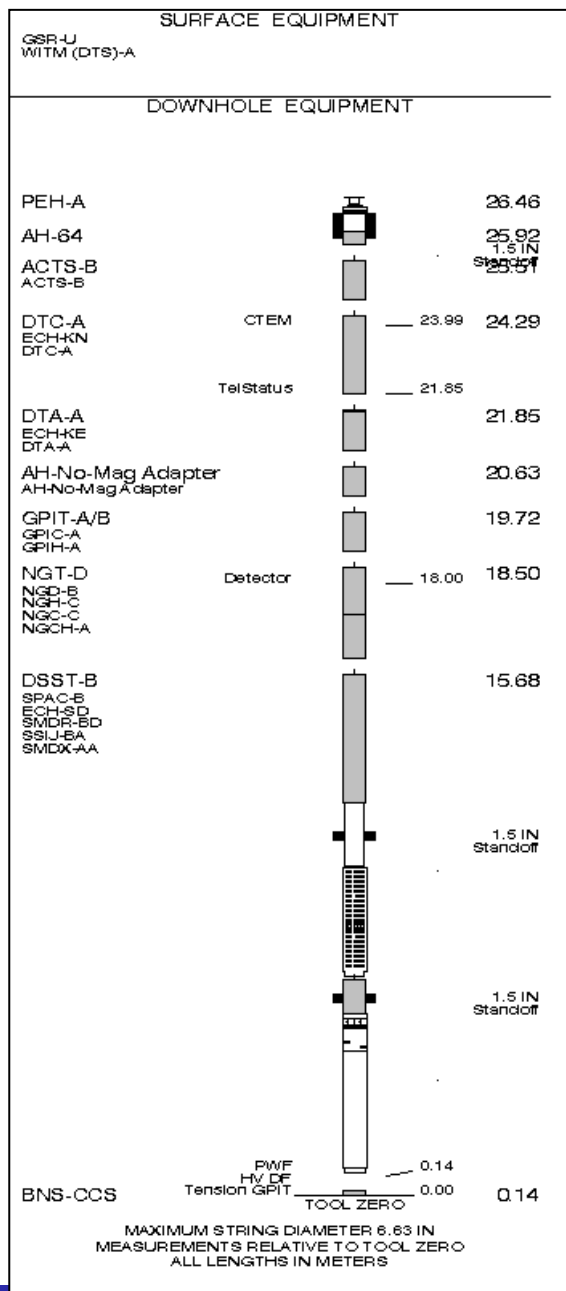
LOGGING OPERATION

- Logging Unit
- Conductor Wireline
- Logging Instrument



Country: EGYPT

OTHER SERVICE BS1			OTHER SERVICE BS2		
OS1:	HALS-TLD-APS-HNGS		OS1:		
OS2:	BGL-DSH-GR		OS2:		
OS3:	LDL-CMR-GR		OS3:		
OS4:	MDT-GR		OS4:		
OS5:	VSP-GR		OS5:		
REMARKS: RUN NUMBER 1					
First run in hole. Schlumberger depth control policy applied.					
Cable stretch correction 0.7 M was applied.					
IDW used as primary depth reference.					
All wireline data provided by the client.					
Toolstring run as per tool sketch. Resistivity recorded with 2" Stand off.					
ACTS was run to record down hole head tension.					
Log data recorded in High Resolution mode.					
HGNS was used as telemetry mode for TLD. No data recorded.					
Caliper check inside casing was done as per formal log.					
Logging interval as per clients request.					
Maximum recorded temperature 55.55 DegC.					
-					
Additional IR data:					
Salinity: 49,000 Kppm, Hg/Grauity/Solid 11.3 %Vol,					
RUN 1			RUN 2		
SERVICE ORDER #:			SERVICE ORDER #:		
PROGRAM VERSION:			PROGRAM VERSION:		
FLUID LEVEL:			FLUID LEVEL:		
LOGGED INTERVAL	START	STOP	LOGGED INTERVAL	START	STOP



Planning - Acquisition

- An accurate **planning** is the key not only to a successful acquisition, but also to assure the maximum return from the acquired data
- Different logging tools can be combined in a single string to reduce the number of runs, but not all tool combinations are possible
- The total length of the string also must be considered (specially in deviated wells)
- Recent tools bypass these problems by providing different services in a single run (Platform Express)

Log Quality Control (LQC)

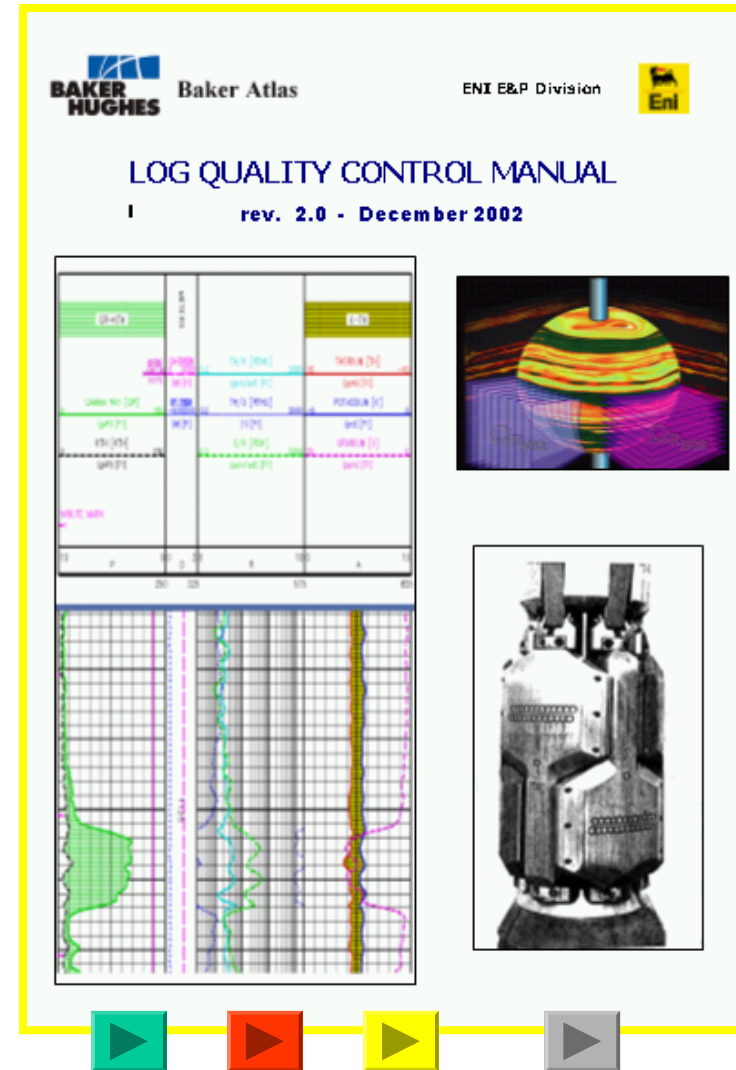
The goal of well logging is to acquire high quality data in order to produce a robust formation evaluation

Log Quality Control consists in verifying the quality of data against initial requirements, as specified in the Logging Program, and according to the indications defined in the Quality Control Manual

Log Quality Control is done with regard to:

- data presentation
- tool calibration
- operational techniques
- analogical data quality
- digital data quality
- time losses and operational efficiency

Log Quality Control at the wellsite is necessary to recognize and satisfy the need for immediate action (relogging, etc.)



Eni's Way

Petrophysical Parameters

- The main petrophysical parameters that can be estimated from well logs are:
- Porosity Φ (total porosity, effective porosity)
- Permeability (**K**)
- Water Saturation (**S_w**, **S_{wi}**)
- The thickness of the productive layers can also be detected in order to evaluate *gross pay*, *net pay* and *net/gross*.

Petrophysical Parameters

- The petrophysical parameters estimated from well logs are used to compute the volume of hydrocarbon originally in place

$$\text{HOIP} = \frac{\text{N/G} \bullet \text{GBV} \bullet \Phi \bullet (1-S_w)}{\text{FVF}}$$

- GBV = Gross bulk volume
- Φ = Effective porosity in %
- $1 - S_w$ = Initial oil saturation
- FVF = Formation volume factor (B_o for oil)

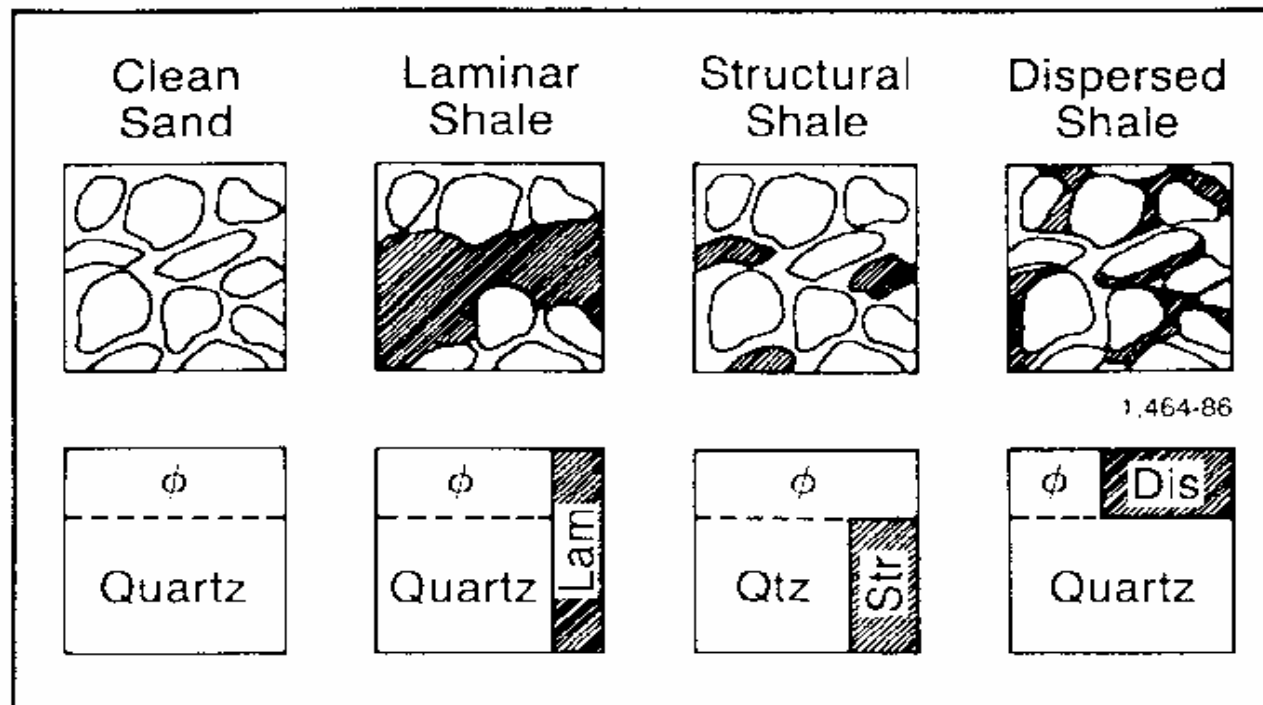
Porosity

- **Porosity** is the pore volume per unit volume of formation; it is the fraction of the total volume that is occupied by pores or voids
- Porosity can be evaluated from porosity logs (Density, Neutron, Sonic, Dielectric e Nuclear Magnetic Resonance)
- Well logs measure the total porosity (Φ_t), while the effective porosity (Φ_e) is computed through an empirical relationship concerning Φ_t , Φ_e e V_{sh} (shale volume)
 - For laminated shales $\Phi_e = \Phi_{tsand} * (1 - V_{sh})$

Silt, Clay and Shale

- **Silt** : fine grains of feldspars, quartz, mica, carbonates, heavy minerals (mineralogical definition)
- **Clay** : very fine grains (Kaolinite, Illite, Montmorillonite) with a high surface/volume ratio. Irreducible water tends to cling to clay
- **Shale** : a mixture of clay and silt. It is characterised by high porosity and very low permeability

Total and Effective Porosity



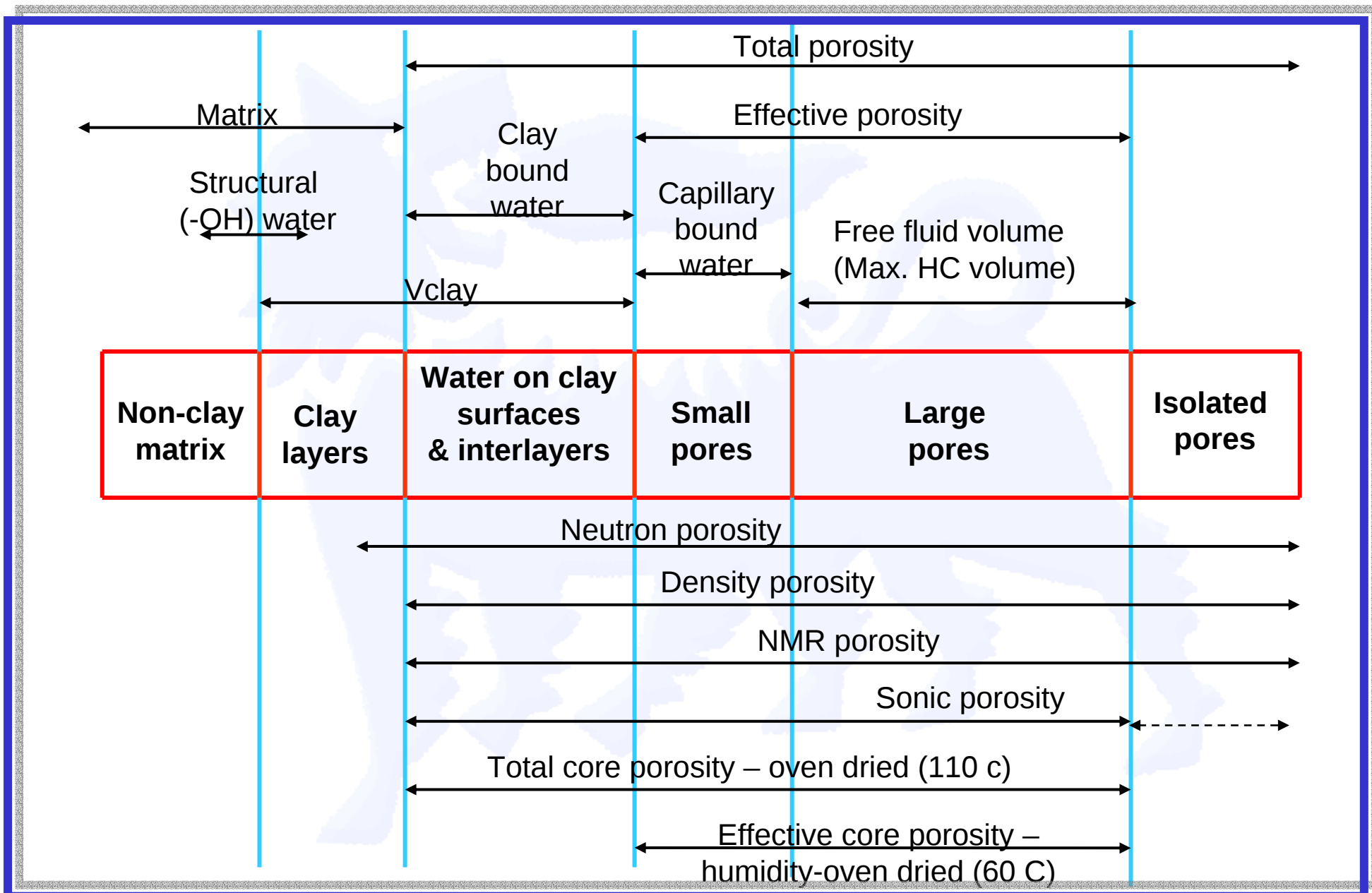
*Figure E1: Forms of Shale Classified by Manner of Distribution in the Formation
Pictorial Representations Above, Volumetric Representations Below*

Total and Effective Porosity

- We consider three different types of shale:
 - Laminar
 - Structural
 - Dispersed
- Accordingly, given V_{shale} and Φ_t , we estimate Φ_e
 - Clean sand : $\Phi_e = \Phi_t$
 - Laminar shale : $\Phi_e = \Phi_t * (1 - V_{\text{lam}})$
 - Structural shale : $\Phi_e = \Phi_t$
 - Dispersed shale : $\Phi_e = \Phi_t - V_{\text{dis}}$

Some Porosity Definitions

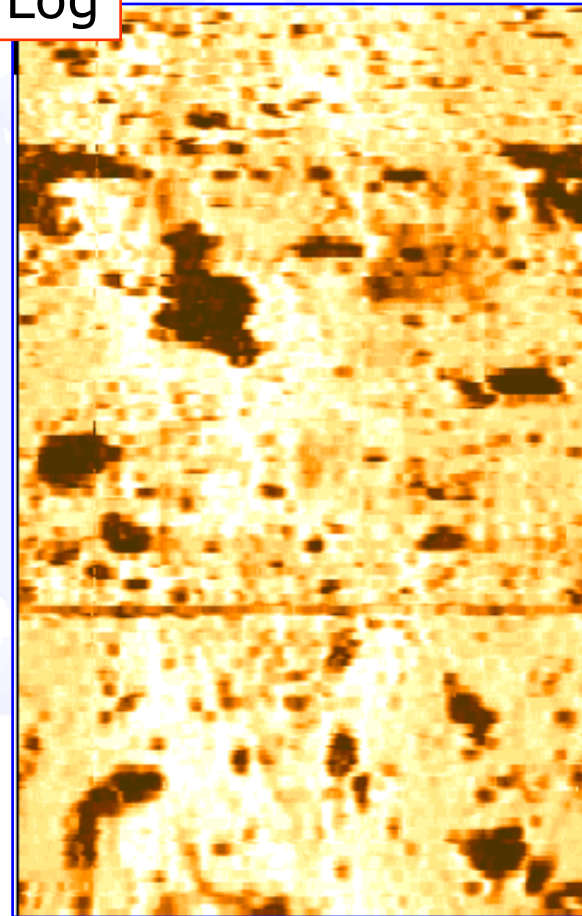
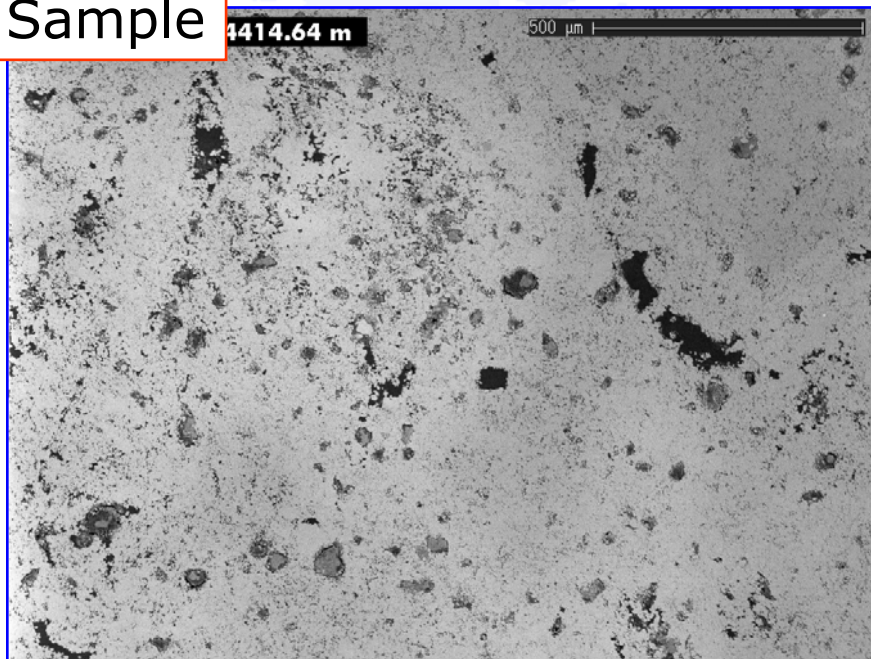
- **Total porosity:** total water content. Clay bound water + capillary bound water + free fluid, including isolated porosity
- **Effective porosity:** Total porosity less clay bound water
- **Clay bound water:** water associated with clay
- **Capillary bound water** (irreducible water saturation): part of the effective porosity that contains unmovable water
- **Free fluid:** volume of free fluid, pore space available to hydrocarbons



Isolated Pores

Image Log

Sample



Permeability

- **Permeability** is a measure of the ease with which fluids can flow through a formation
- For a given sample of rock and for any homogeneous fluid, the permeability will be a constant provided the fluid does not interact with the rock itself
- The unit of permeability is the Darcy (D)
- A permeability of 1 Darcy is defined as the permeability which allows a fluid of 1 cp viscosity to flow through a section of 1 cm², with the rate of 1 cm³/sec, under a pressure gradient of 1 atm/cm

Geology & Permeability

- Sand / Shale
 - Stratification
 - Grain size distribution and sorting
 - Clastic bodies shape and orientation
 - Packing
 - Cementation
 - Shale content volume
- Carbonates
 - Diagenesis
 - Porosity development
 - Presence, size and orientation of fractures

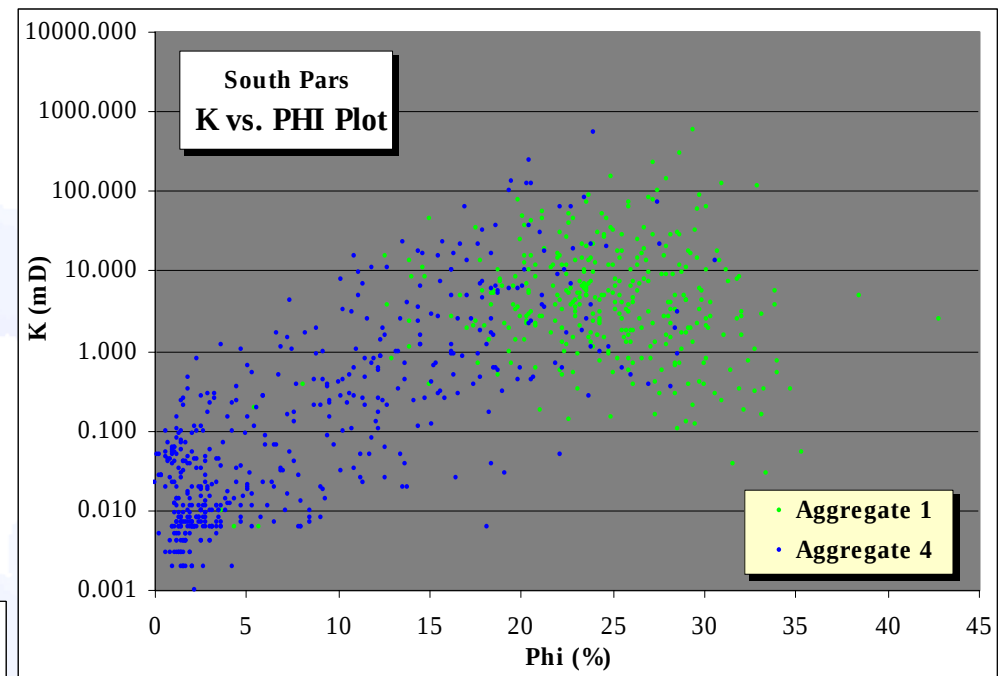
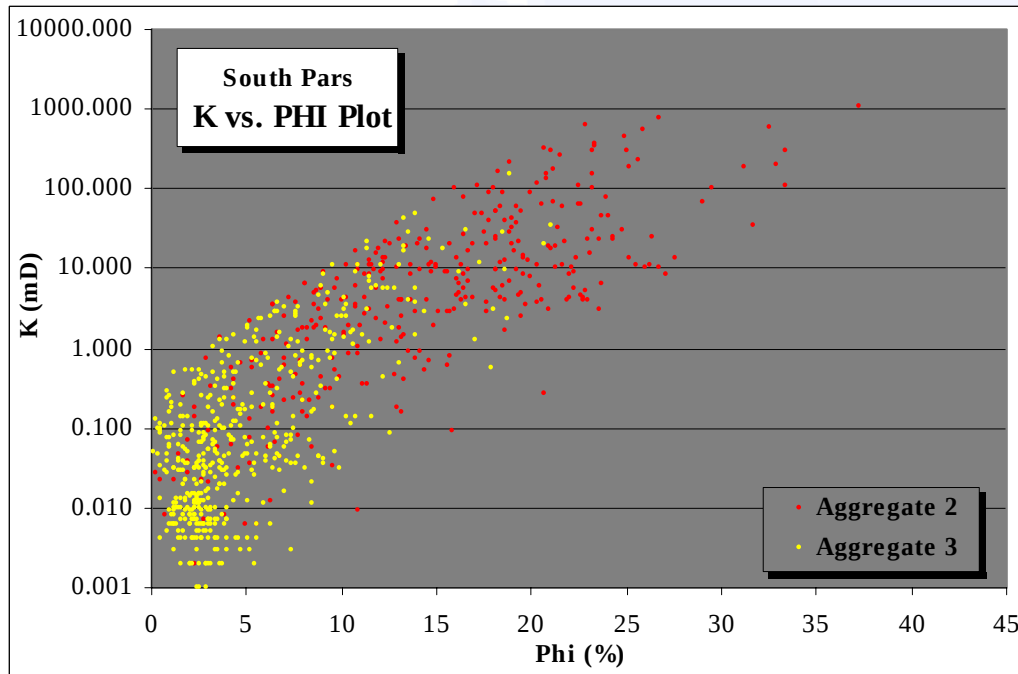
Relationship Between Porosity and Permeability

- In order to be permeable, a rock must have some interconnected pores, capillaries, or fractures
- Hence, there exists some rough relationship between porosity and permeability
- Greater permeability, in general, corresponds to greater porosity, but this is far from being an absolute rule

Relationship Between Porosity and Permeability

- Shales and some sands may have high porosities, but the grains are so small that the paths available for the movement of fluid are restricted and tortuous; thus, their permeability may be very low
- Other formations, such as carbonates, may be composed of a dense rock broken by a few small fissures or fractures of even great extent. The porosity of such a formation can be low, but the permeability of a fracture can be enormous.

relationships porosity permeability
Are complex almost in carbonates



Water Saturation (S_w)

- **Water Saturation** (S_w) is the fraction of pore space filled by formation water
- Hydrocarbon Saturation (S_h) therefore is:

$$S_h = 1 - S_w$$

- The evaluation of S_w is based on porosity and formation resistivity

Irreducible Water Saturation (S_{wi})

- The water saturation of a formation can vary from 100% to a quite small value, but it is seldom, if ever, zero
- Because of capillary forces, a small amount of water always clings to the grains of the rock and cannot be displaced by the oil
- This saturation is generally referred to as irreducible or connate water saturation (S_{wi})
- A formation at irreducible water saturation will produce water-free hydrocarbons

Resistivity

- **Ohm** law defines the flux of current as:

$V = r I$ V =differential potential (volt)

r =resistance (ohm)

I =intensity of the current (ampère)

- **Resistivity** of a medium is the resistance to the flux of current measured between two opposite faces of a cube (1 meter length):

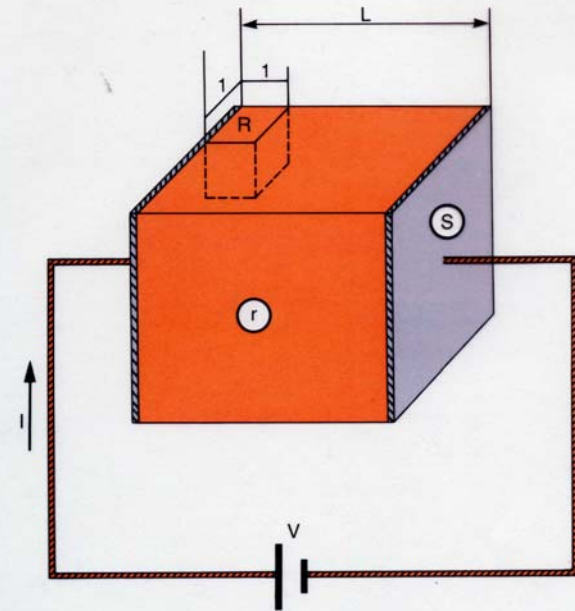
$R = r S / L$ R =resistivity (ohm.m)

r =resistance (ohm)

L =length of the cube (m)

S =surface area face of the cube (m²)

Basics of Resistivity



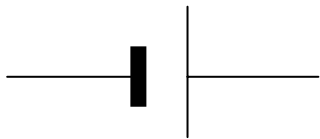
$$V = r I \quad \rightarrow \quad R = \frac{S}{L} \frac{V}{I}$$
$$r = R \frac{L}{S}$$

$$R = K \frac{V}{I}$$

Resistivity

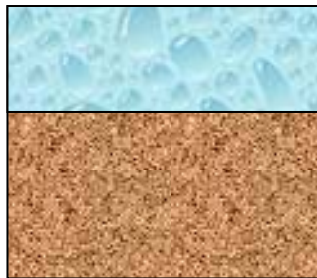
- The electrical resistivity of a substance is its ability to impede the flow of electrical current
- In most cases rocks, when dry, will not conduce an electrical current: the rock matrix has zero conductivity or infinitely high resistivity
- An electrical current will flow only through the interstitial water saturating the pore structure of the formation, and then only if this water contains dissolved salts
- The greater the porosity of the formation and, hence, the greater amount of formation water, the lower the resistivity

$V = \text{constant}$



$$\text{PHI} = 100\%$$

$$R_w = V/I_1$$



$$\text{PHI} = 30\%$$

$$S_w = 100\%$$

$$R_o = V/I_2$$

$$R_o > R_w$$



$$\text{PHI} = 30\%$$

$$S_w = 20\%$$

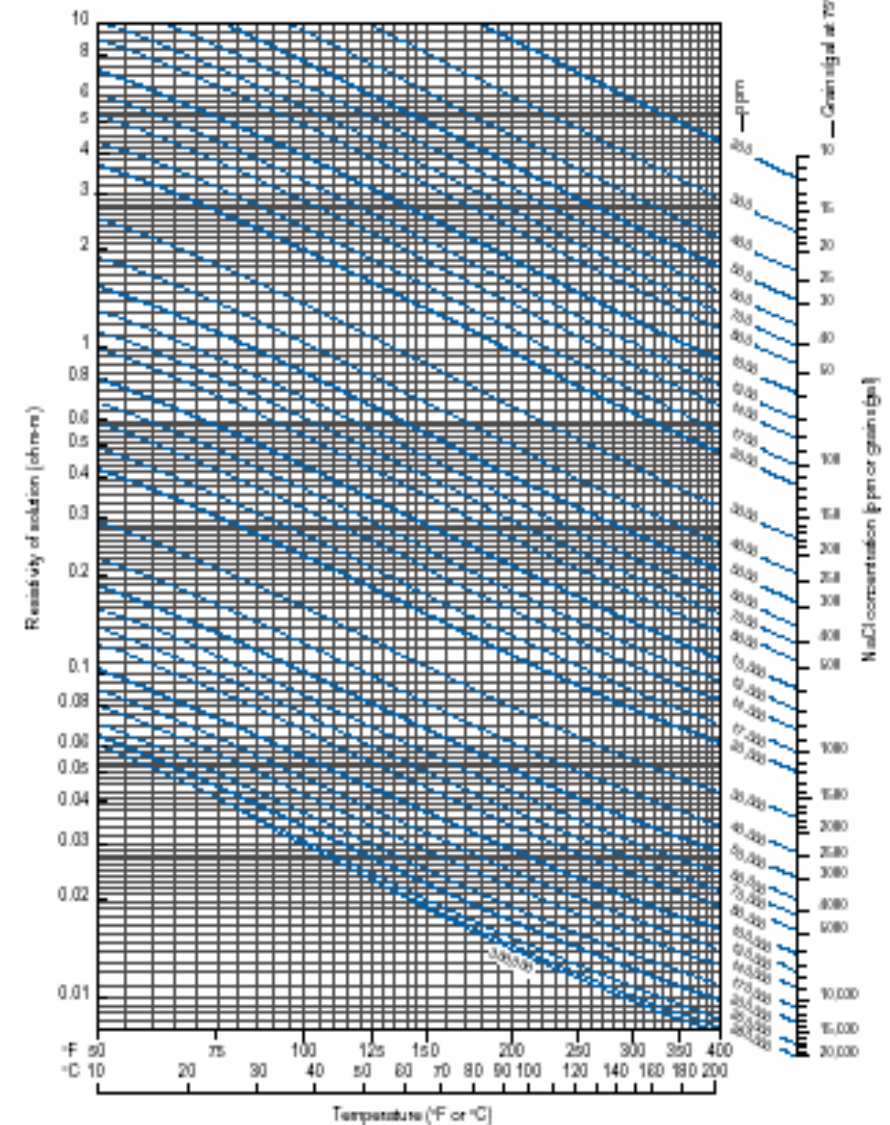
$$R_t = V/I_3$$

$$R_t \gg R_o$$

Resistivity of NaCl Solutions



Conversion approximated by $R_2 = R_1 [(T_1 + 8.77)/(T_2 + 8.77)]^F$ or $R_2 = R_1 [(T_1 + 21.5)/(T_2 + 21.5)]^C$



Formation Factor

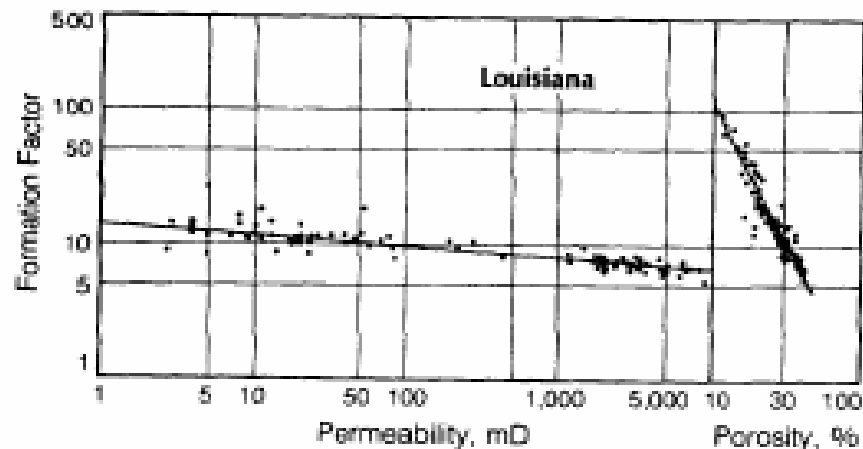
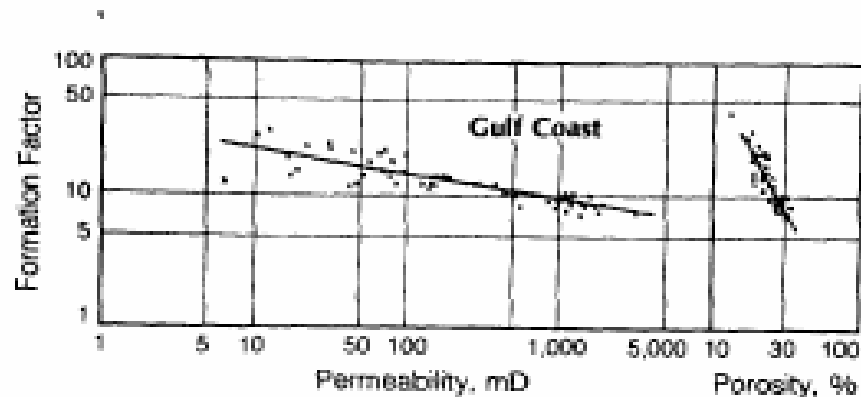
- The resistivity of a clean, water-bearing formation, R_0 , is proportional to the resistivity of the brine, R_w , with which it is fully saturated
- The constant of proportionality is called the **formation resistivity factor** (F)

$$F = R_0 / R_w$$

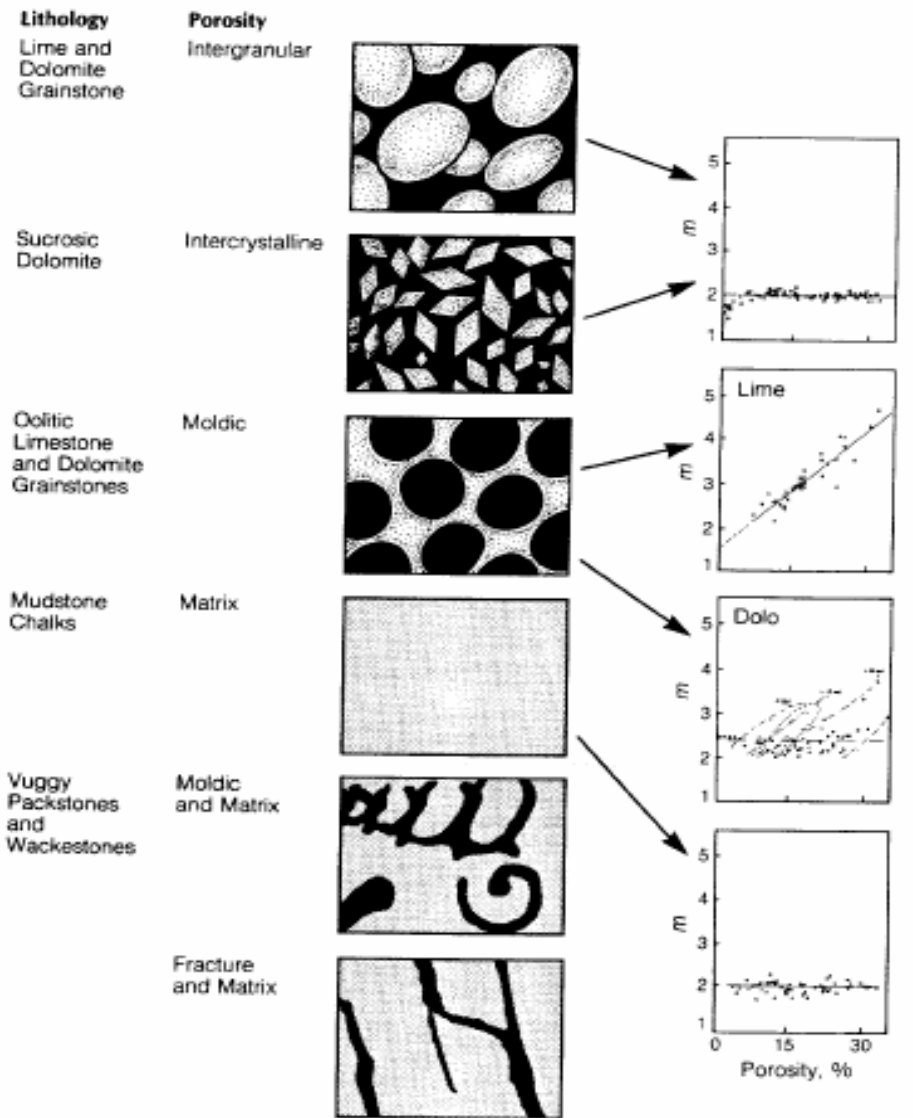
- Formation factor is inversely proportional to porosity; **Archie** proposed an empirical relationship between porosity and F:

$$F = a / \Phi^m$$

Formation Factor: porosity/resistivity relationship



□ Archie's plots of electrical formation factor, F , versus permeability, K , and porosity, ϕ , for Gulf Coast and Louisiana sandstones. The linear porosity trends prompted him to suggest $F = \frac{1}{\phi^m}$ as a general relationship. Porosity exponent m is a constant. (From reference 1.)



Sw Evaluation

Archie Equation for “Clean Rocks”

$$R_t = (F * R_w / S_w^n),$$

where $F = (1 / \phi_t^m)$ in compacted formations,

so $S_w = ((1 / \phi_t^m) * (R_w / R_t))^{1/n}$

Nomenclature

R_t	= true formation resistivity;
R_w	= formation water resistivity;
S_w	= formation water saturation (pores volume filled by formation water);
F	= formation factor;
ϕ_t	= total formation porosity;
m	= cementation exponent (@ 2 in Archie experiment);
n	= saturation exponent (@ 2 in Archie experiment).

Resistivity

- The presence of **clay / shale** makes difficult interpretations in hydrocarbon-bearing formations
- The type of clay/shale, its volume and its distribution have different effects on resistivity measurements
- The presence of clay/shale inside sand bodies usually lowers the resistivity value thus enhancing water saturation
- According to clay/shale distribution, different equations may be used to compute **S_w** :
 - Simandoux and Indonesia for laminated shale
 - Waxman-Smiths and Dual Water for disperse shale



Well Logs

Keywords

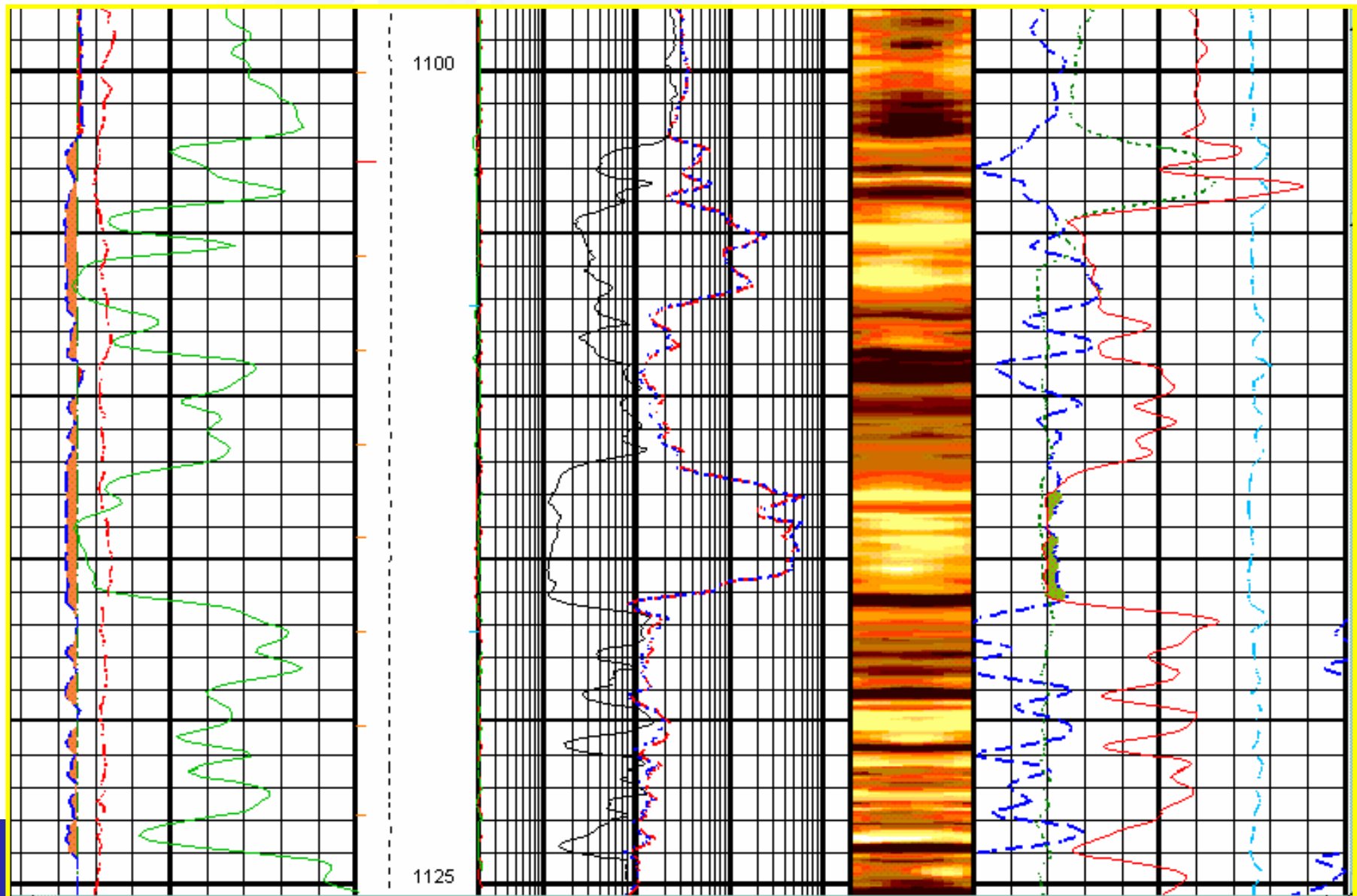
What are they? What do they measure?

Well Logs: What Are They?

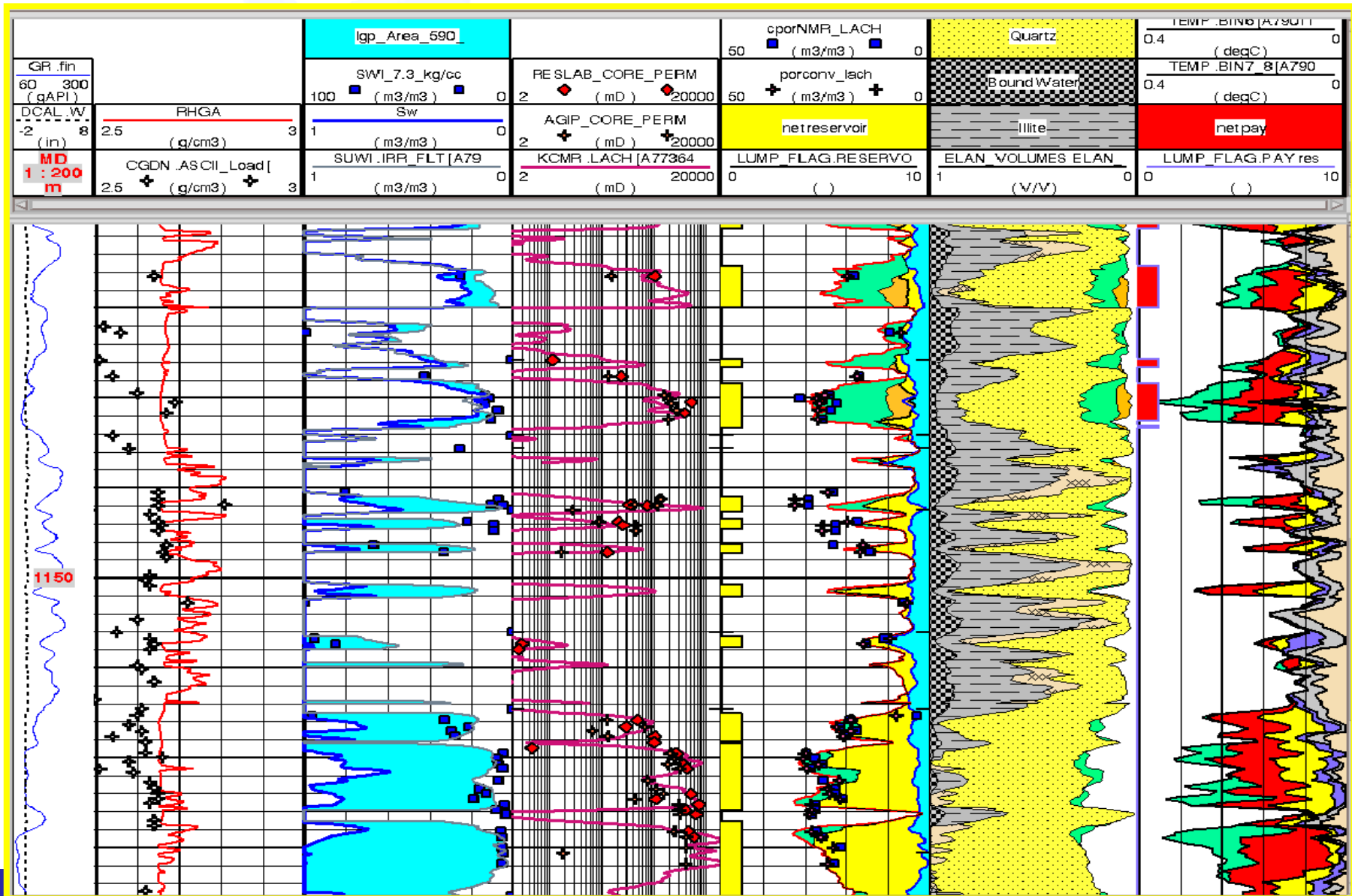
Caliper - GR

Resistivity

Density/Neutron



Well Logs: What Can They Be Used For?



**Field Log
Digital Data**

**Quality
Control**

**Editing
Normalization**

Signals

Interpretation

Tool

Formation

Petrophysics

Geology

Geomechanics

Well Logs: What Can They Be Used For?

- The physical properties of the rocks are, in general, defined by their mineralogical composition, texture and fluids. Therefore well logs give us important information not only of **petrophysical** type but also of **geological** type.
- The geological characteristics that can be derived from logs are:
 - Compositional
 - Textural
 - Structural

Well Logs: What Can They Be Used For?

- **Composition (Lithology)**
 - SP, GR, Density, Sonic
- **Texture**
 - Image logs, Sonic, Dipmeter
- **Structure**
 - Image logs
- **Fluids**
 - Resistivity, SP, EPT, Neutron, Density, NMR, Sonic
- **Permeability**
 - Resistivity, SP, EPT, Neutron, Density, NMR, Sonic, Caliper

Well Logs: When?

- Well logs can be measured in different phases of the Exploration and Production process:
 - During the drilling phase : Logging While Drilling (**LWD**)
 - After the drilling phase : Open Hole (**OH**) Wire Line Logs (**WLL**)
 - After the well completion and during the productive life of the well : Cased Hole (**CH**) Wire Line Logs

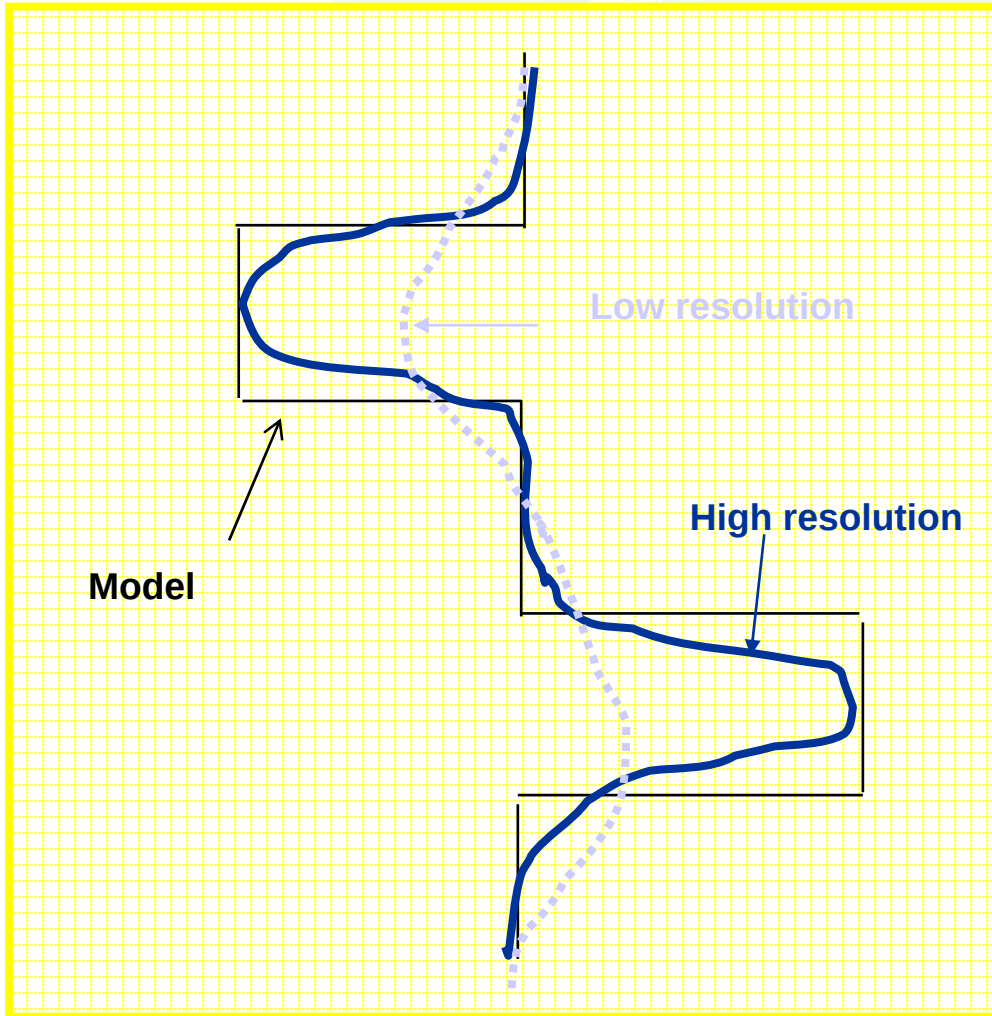
How Can We Get a High Value of Information from Well Logs?

- **Planning Phase - Acquisition**
 - When (Logging While Drilling, Logging Wireline)
 - What (Fit-for-purpose tool selection)
 - How (Acquisition parameters)
- **Log Quality Control**
 - Check how the tool worked against borehole conditions, mud system, well deviation, etc.
- **Interpretation**
 - Integrate log measurements with other available data
 - Use correct and robust interpretation models
 - Try to extract all the information a measurement can give

Some Basic Definitions

- **Depth of investigation** is the mean radius around the tool inside which the formations gives the most significant contribution to the measurement
- **Vertical resolution** is the minimum thickness of the layer inside which the average value measured by the log (at layer's central point) is equal to the real value of the physical parameter
 - Depth of investigation and vertical resolution depend on the tool characteristics
 - Generally speaking, high resolution tools have low depth of investigation and vice versa
- **Sampling rate** is the depth interval between to measurements. It is usually constant, and almost never representative of the real tool resolution.

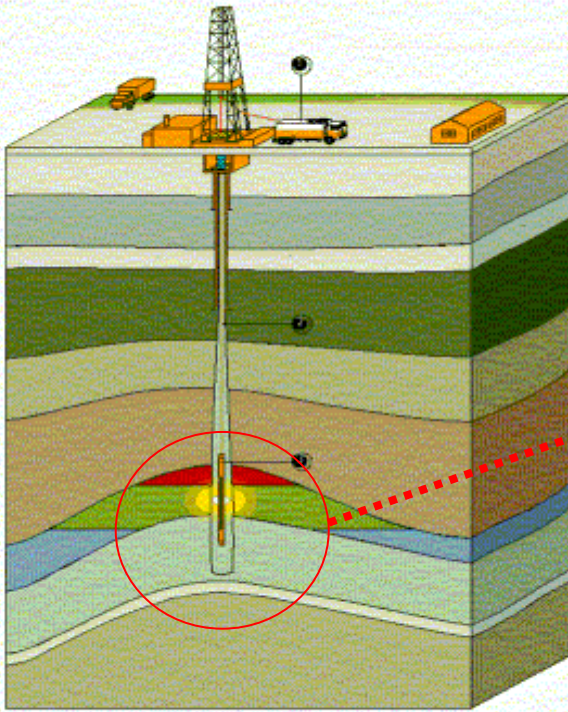
Vertical resolution vs. Depth of investigation



see relationship between
**Resolution and
Depth of investigation**

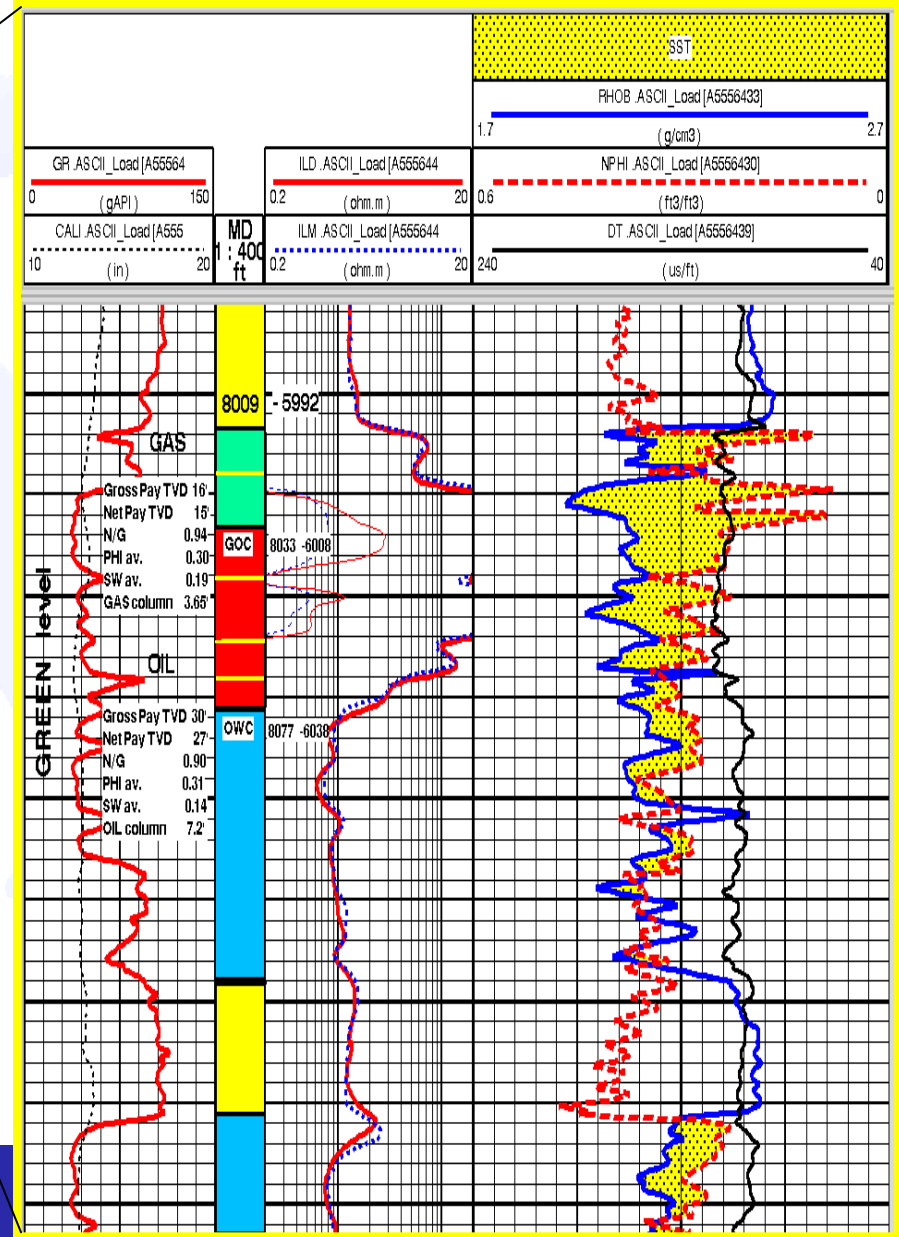
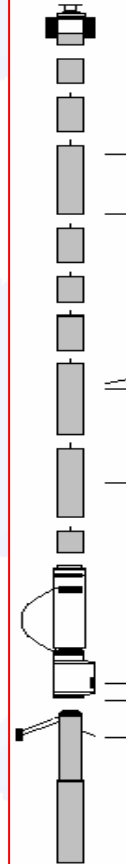
Logging Open Hole

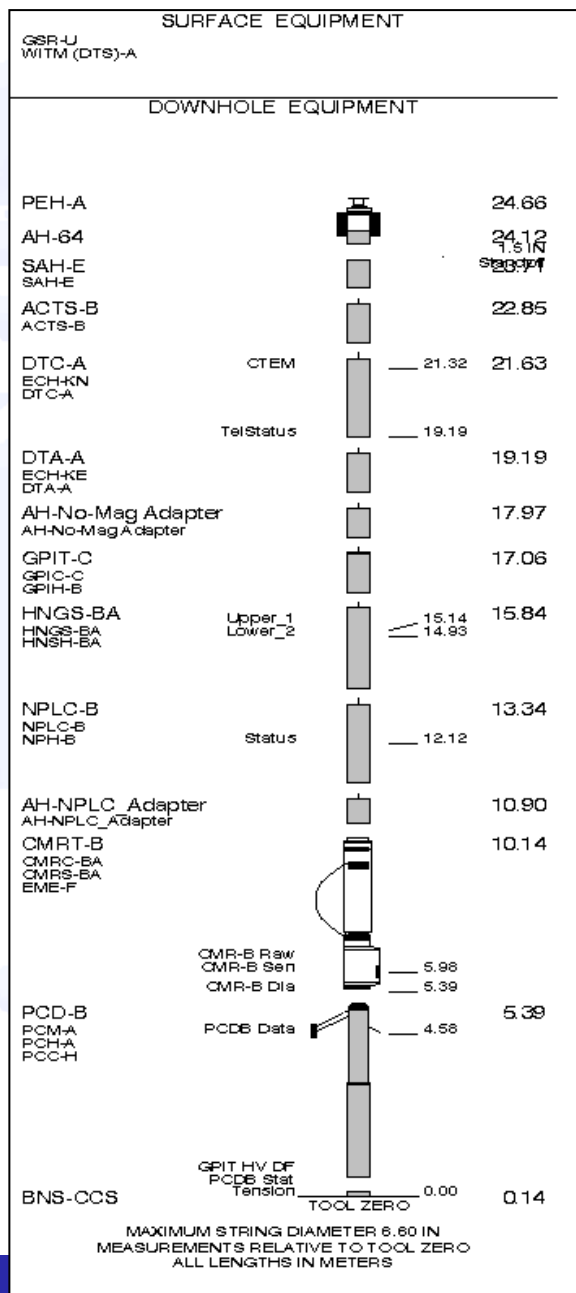
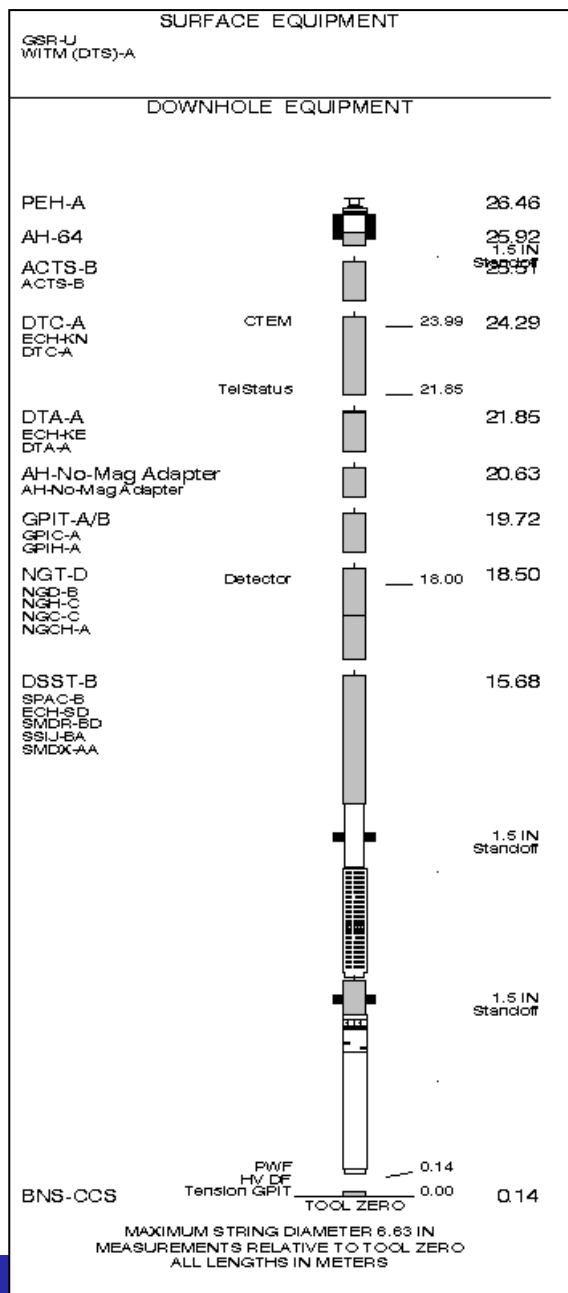
Logging the Well



LOGGING OPERATION

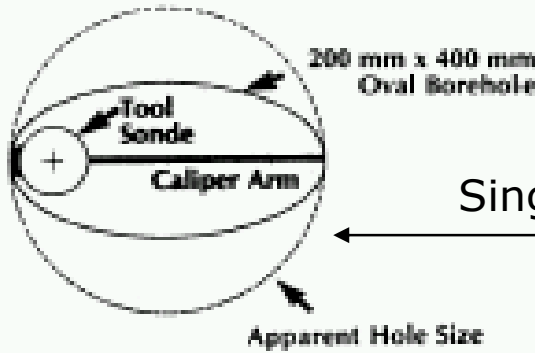
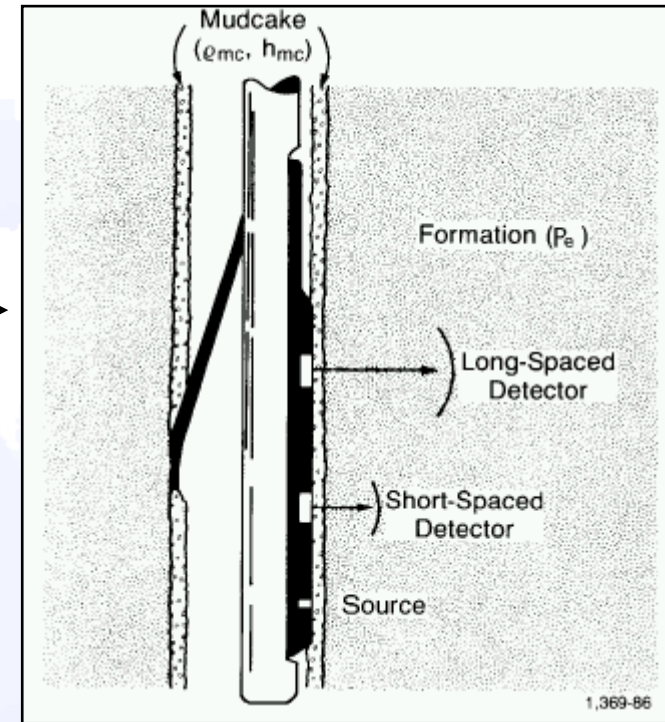
- Logging Unit
- Conductor Wireline
- Logging Instrument



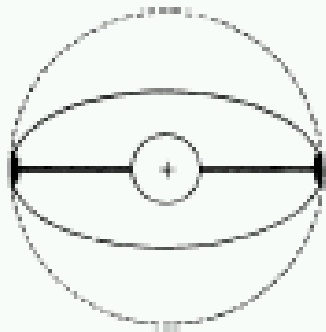


Wire Line OH Logs
typical combinations.

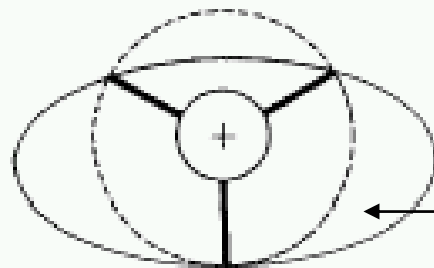
CALIPER



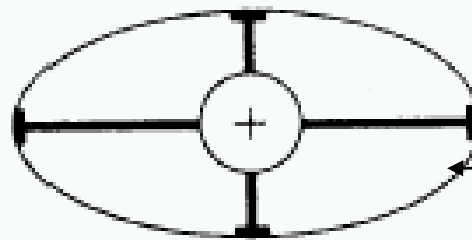
Single arm caliper



Two arm caliper



Three arm caliper



Four arm caliper

To derive LITHOLOGY:

- **Self Potential**
- Gamma Ray and Gamma Ray Spectrometry
- Attenuation of electromagnetic waves

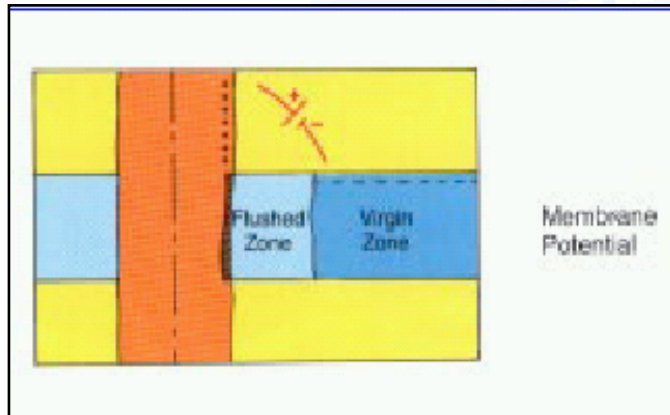
Self Potential (SP)

- **Spontaneous (Self) Potential** is a recording versus depth of the difference between the electrical potential of a movable electrode in the borehole and the electrical potential of a fixed surface electrode
- It records the electrical potential (voltage) produced by the interaction of formation water, drilling fluid and shale. In short it is a function of the contrast between mud salinity and formation water salinity:

$$\text{Static SP} = -K \log (R_{mf}/R_w)$$

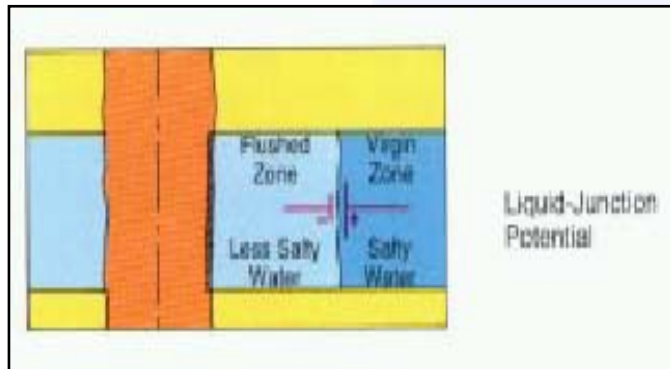
- SP is measured in millivolts (mV)
- SP cannot be recorded in holes filled with resistive mud

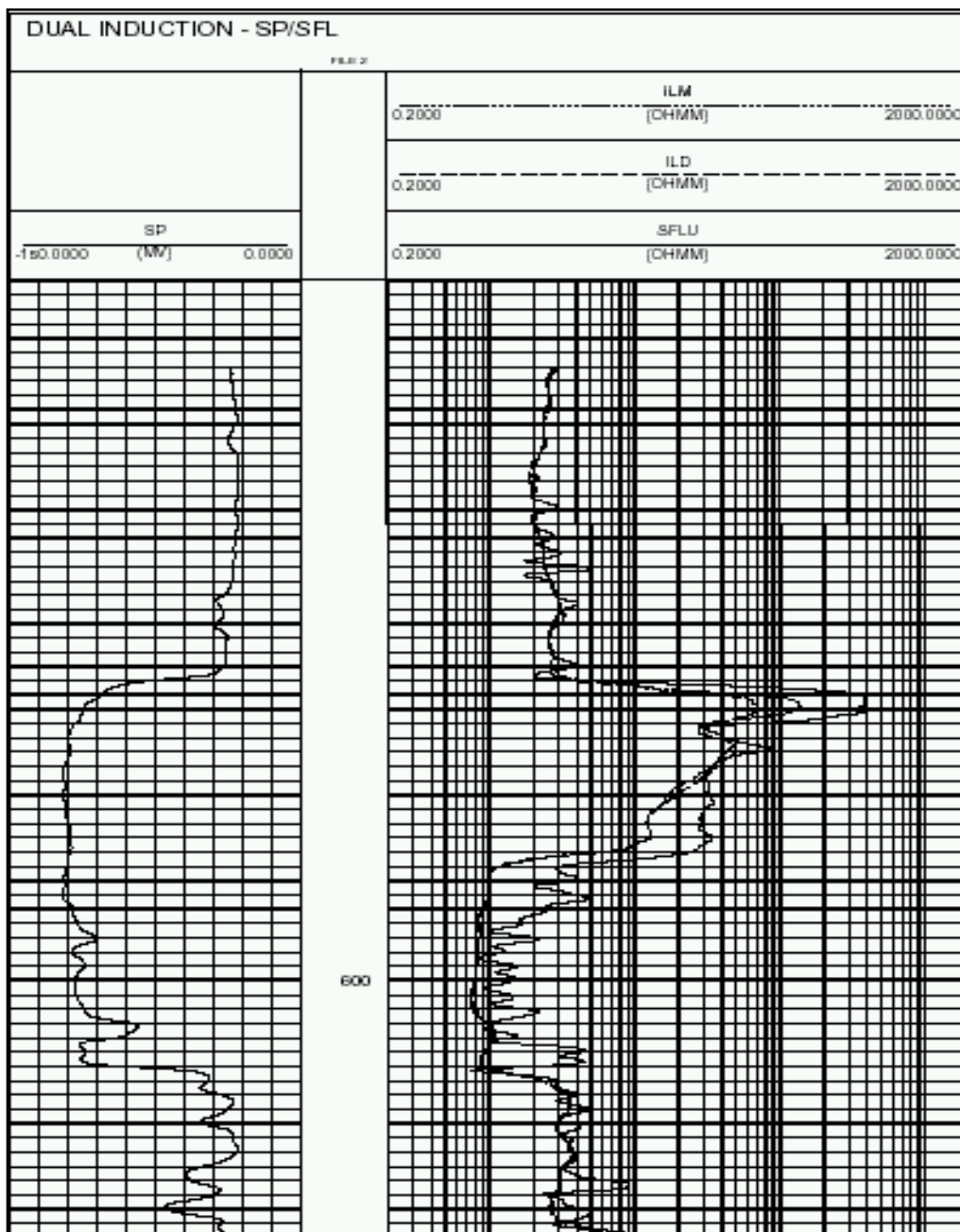
Self Potential (SP)



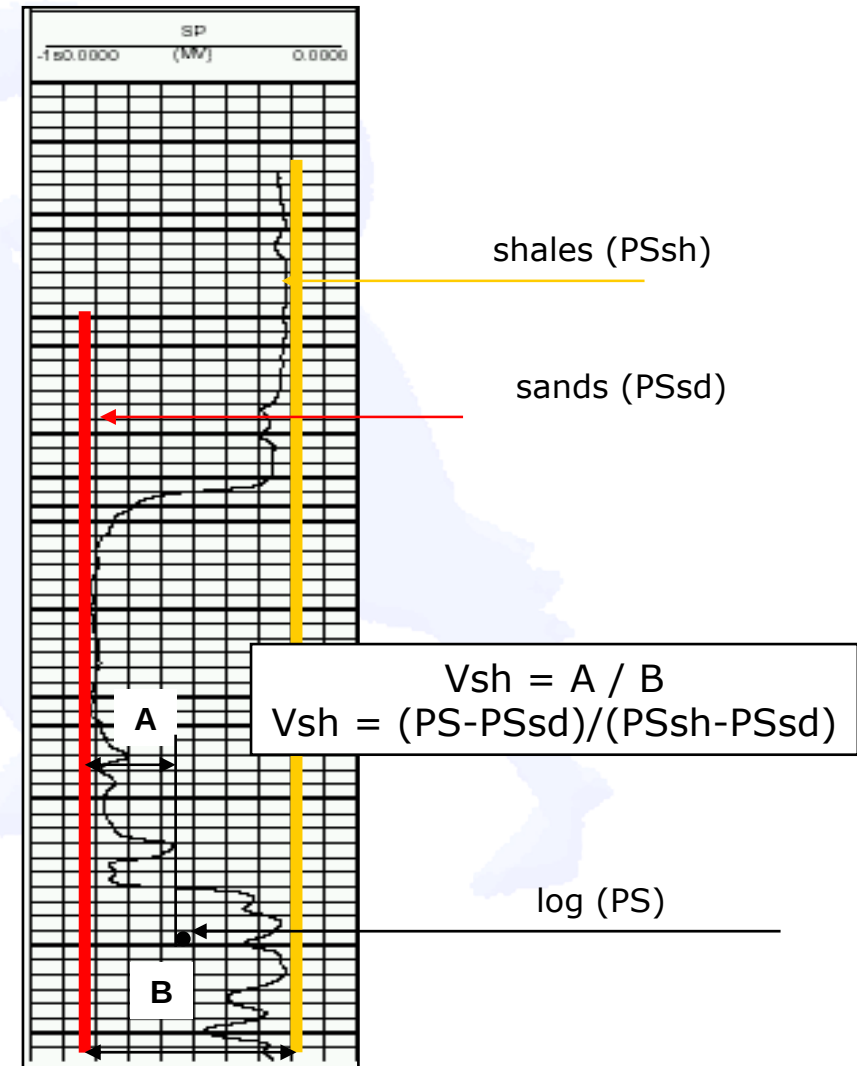
Self Potential is function of the contrast between mud salinity and formation water salinity:

$$SSP = -K \log (R_{mf}/R_w)$$





SP with fresh mud and salty formation water



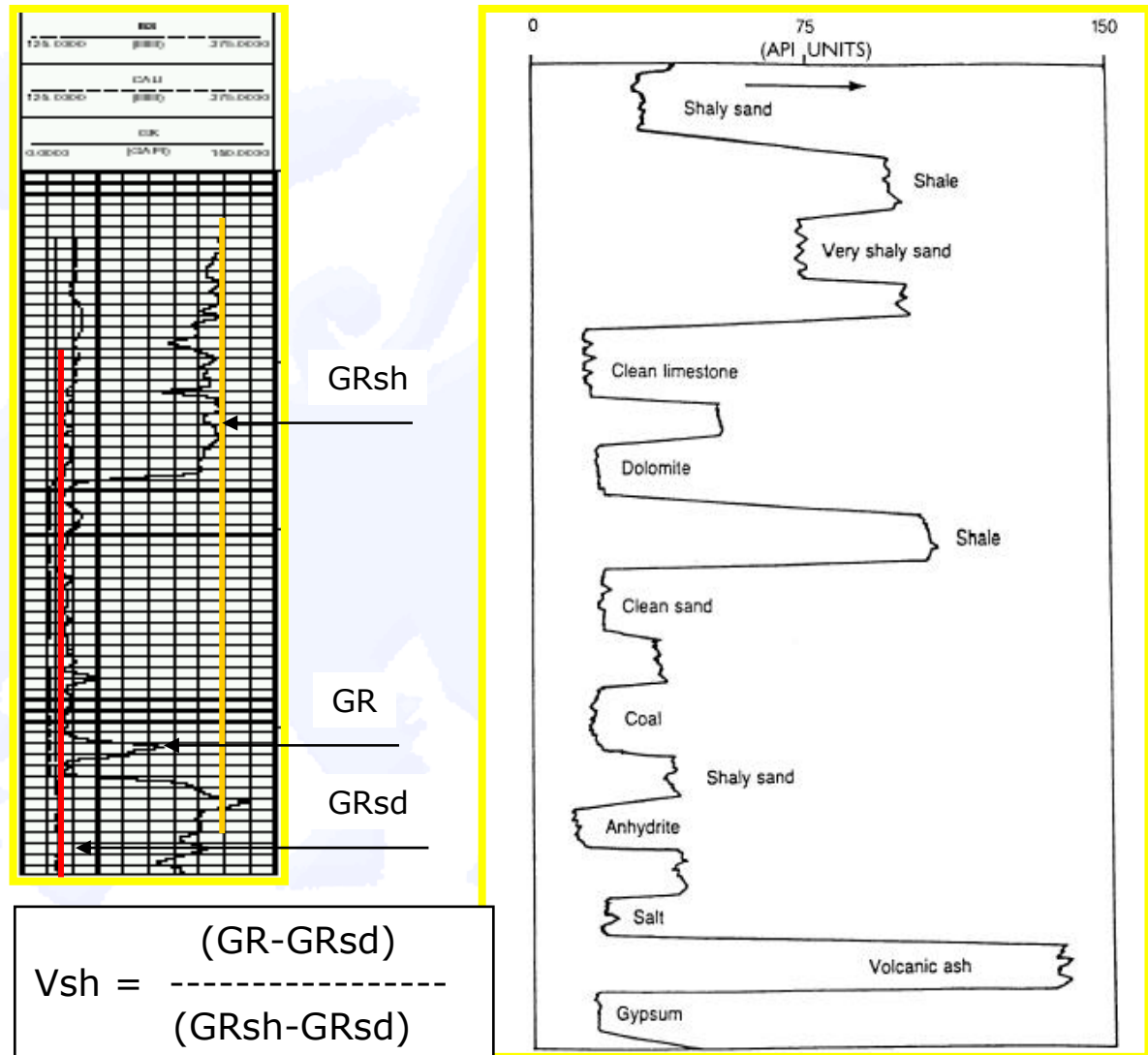
To derive LITHOLOGY:

- Self Potential
- **Gamma Ray** and Gamma Ray Spectrometry
- Attenuation of electromagnetic waves

Gamma Ray (GR)

- The **Gamma Ray** log is a measurement of the natural radioactivity of the formation.
- In sedimentary environments it normally reflects the shale content of the formation, because the radioactive elements tend to concentrate in clays and shales
 - Radioactivity in carbonates is often due to the presence of Uranium and it is not related to the presence of shale
- The GR log can be recorded in cased holes which makes it very useful as a correlation curve

- In sedimentary formations, the depth of investigation of GR is about 1 ft
- GR log is expressed in API units



Gamma Ray energy and calibration

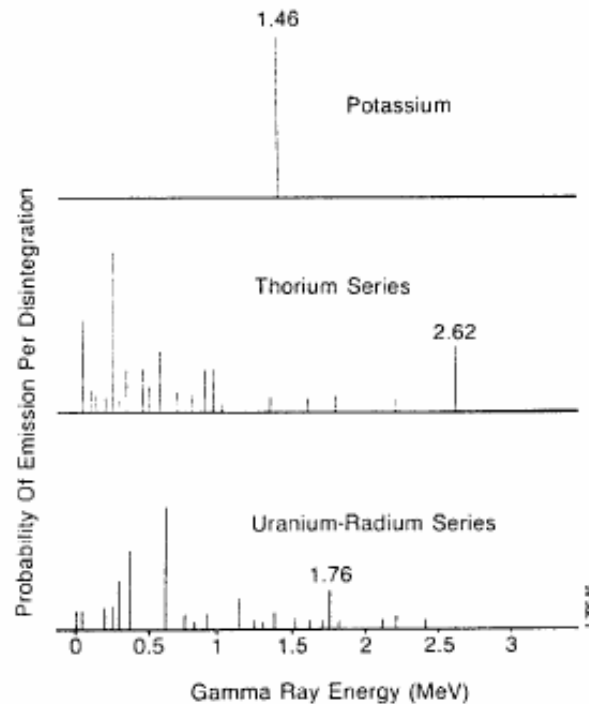


Figure C24: Gamma Ray Emission Spectra of Radioactive Minerals

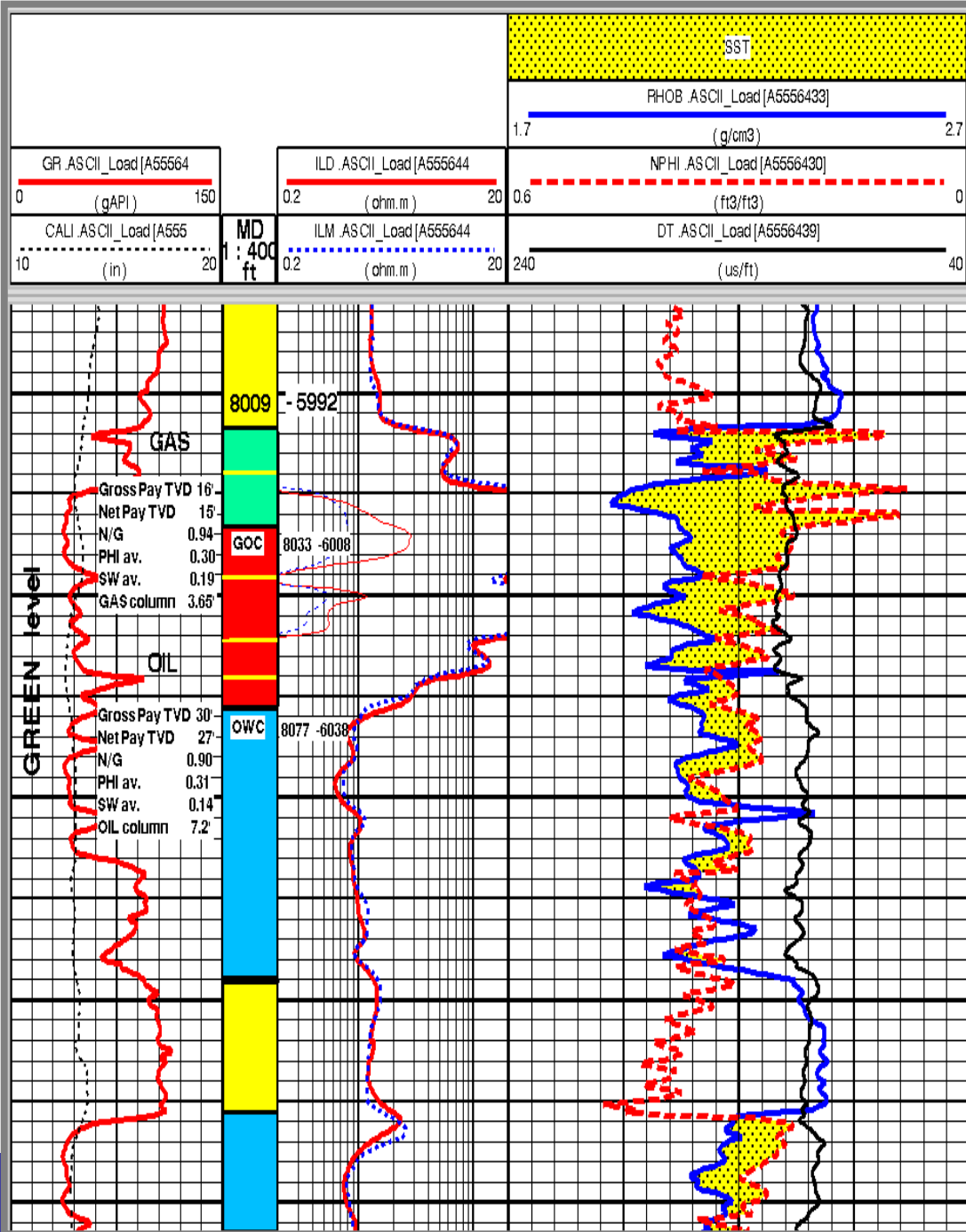
Low activity Cement

High activity Cement

Low activity Cement

K = 4 %
Th = 24 ppm
U = 12 ppm
200 GAPI

Gamma Ray American Institute Test Pit



GR in clastic formations

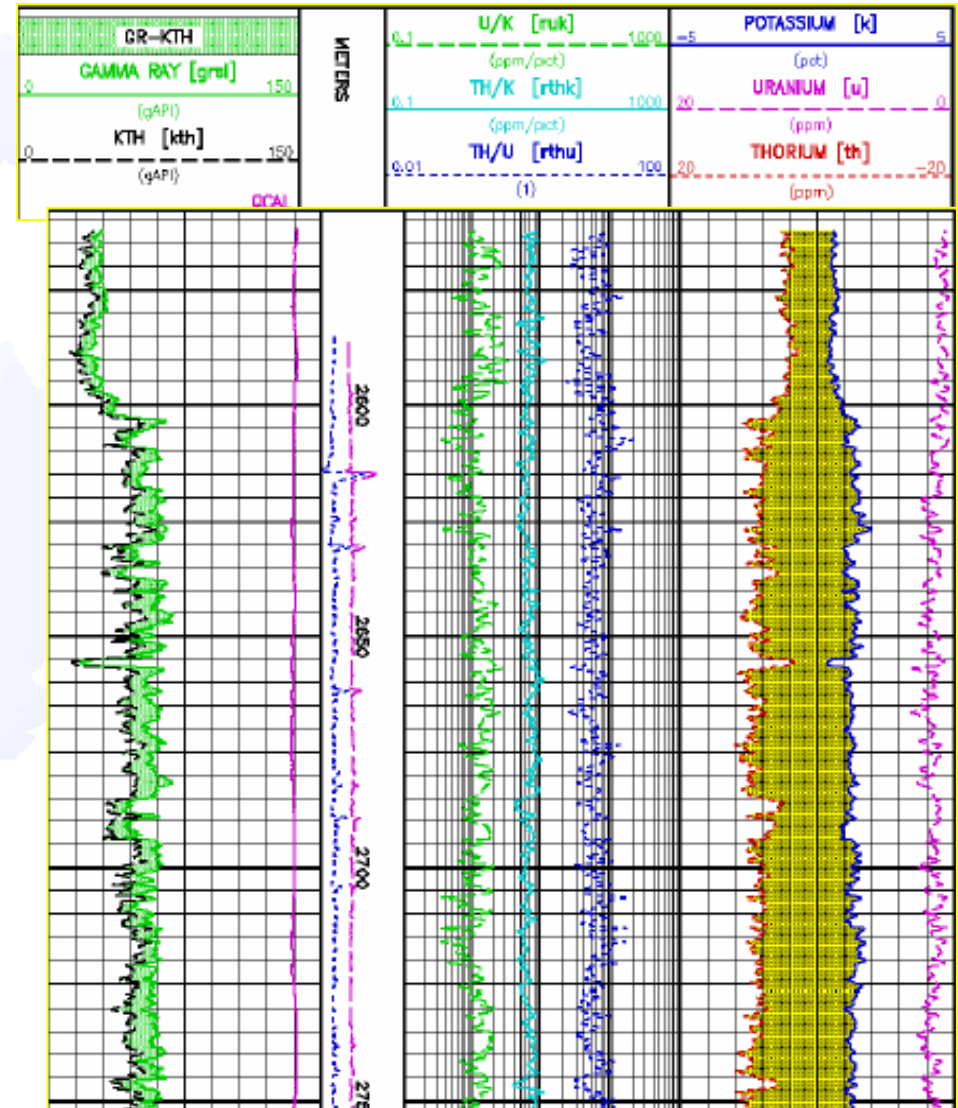
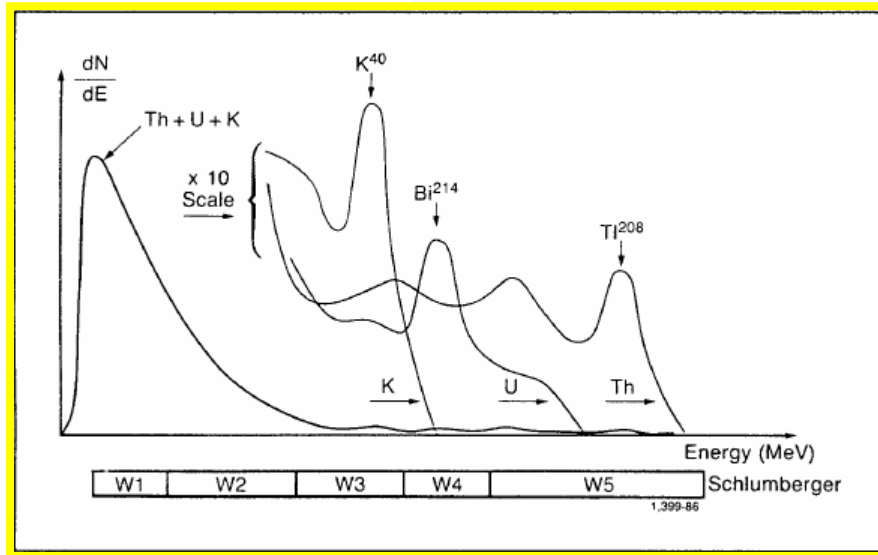


Eni's Way

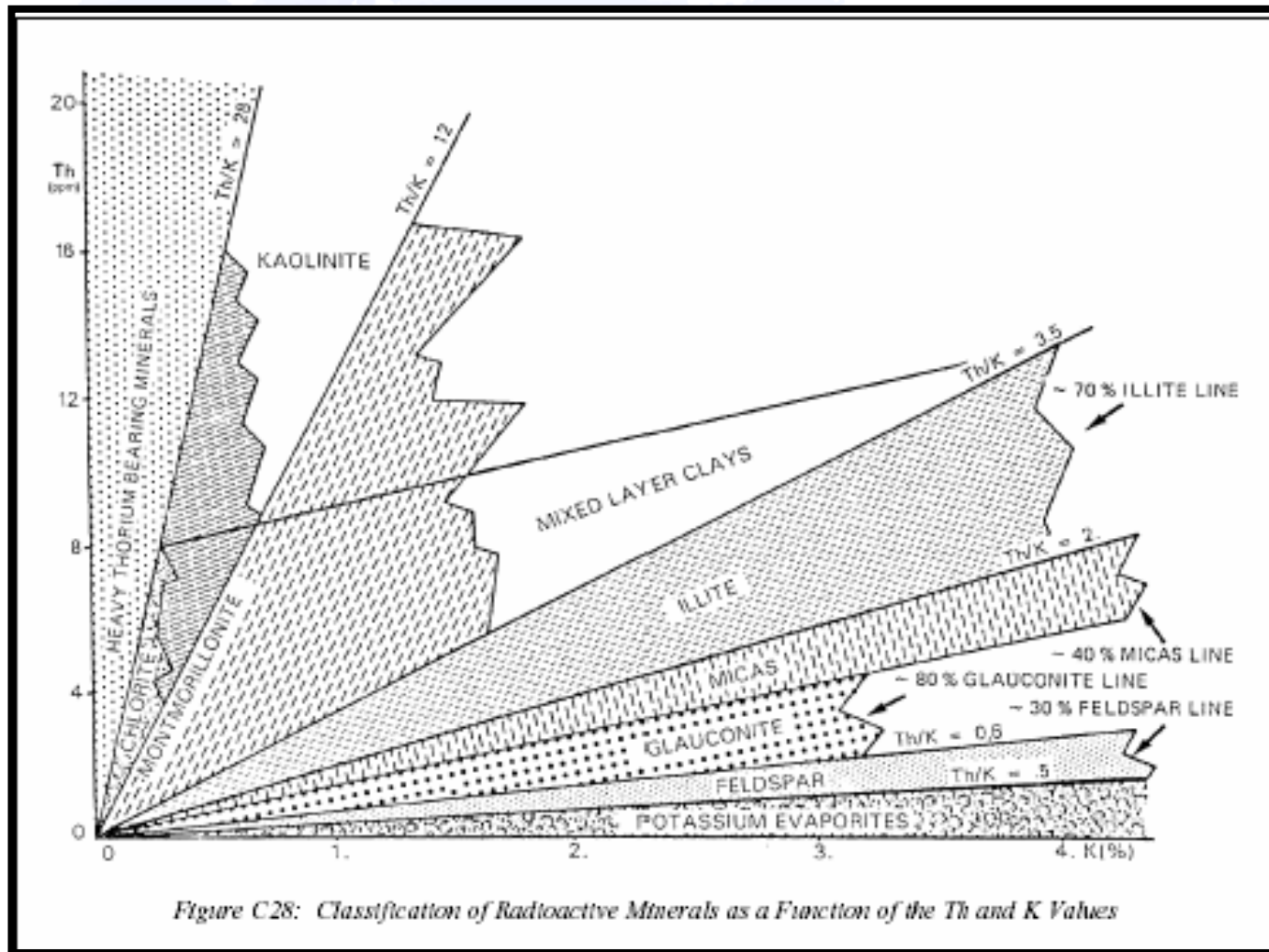
Gamma Ray Spectrometry (NGS)

- The GR log response is proportional to the weight concentrations of the radioactive material
- **NGS** measures both the number of gamma rays and the energy level of each, thus allowing the determination of the concentrations of the radioactive potassium, thorium and uranium in the formation rocks
- GR and NGS logs need to be corrected for borehole effects

Gamma Ray Spectrometry



Mineralogy from Spectral Gamma



To derive LITHOLOGY:

- Self Potential
- Gamma Ray and Gamma Ray Spectrometry
- **Attenuation of electromagnetic waves**

Electromagnetic Propagation Tool (EPT)

It measures the dielectric permittivity of the formation, which is essentially a function of the water-filled porosity

The depth of investigation is very shallow (1 to 6 inches), therefore the water is primarily mud filtrate

EPT logs have high vertical resolution (few cm)

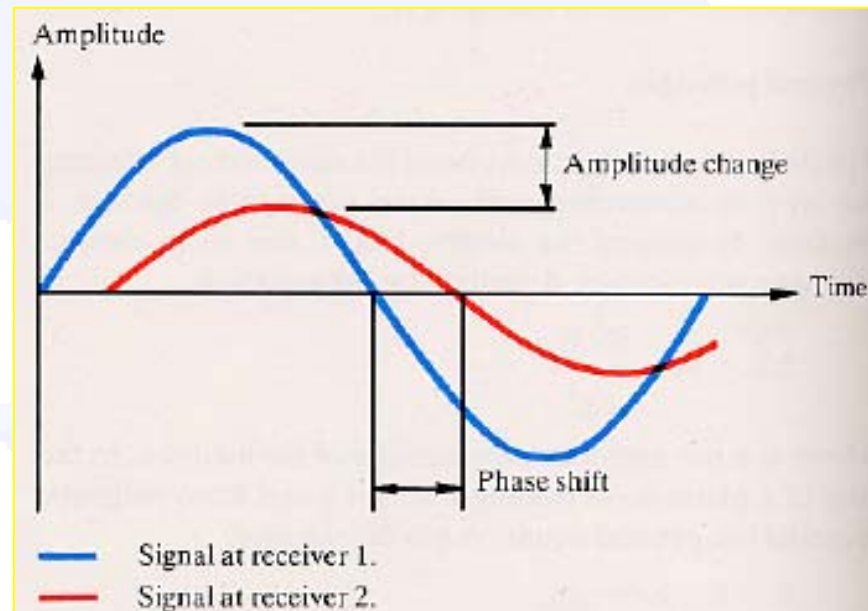
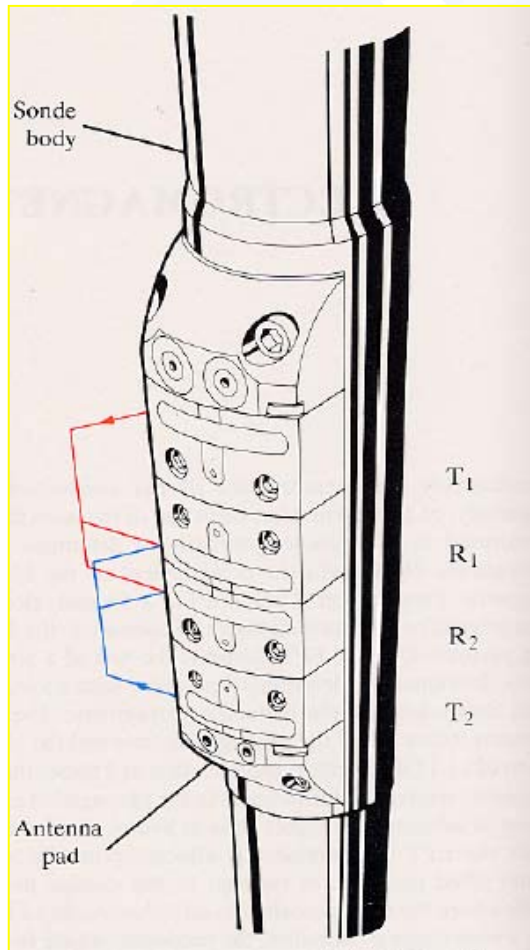


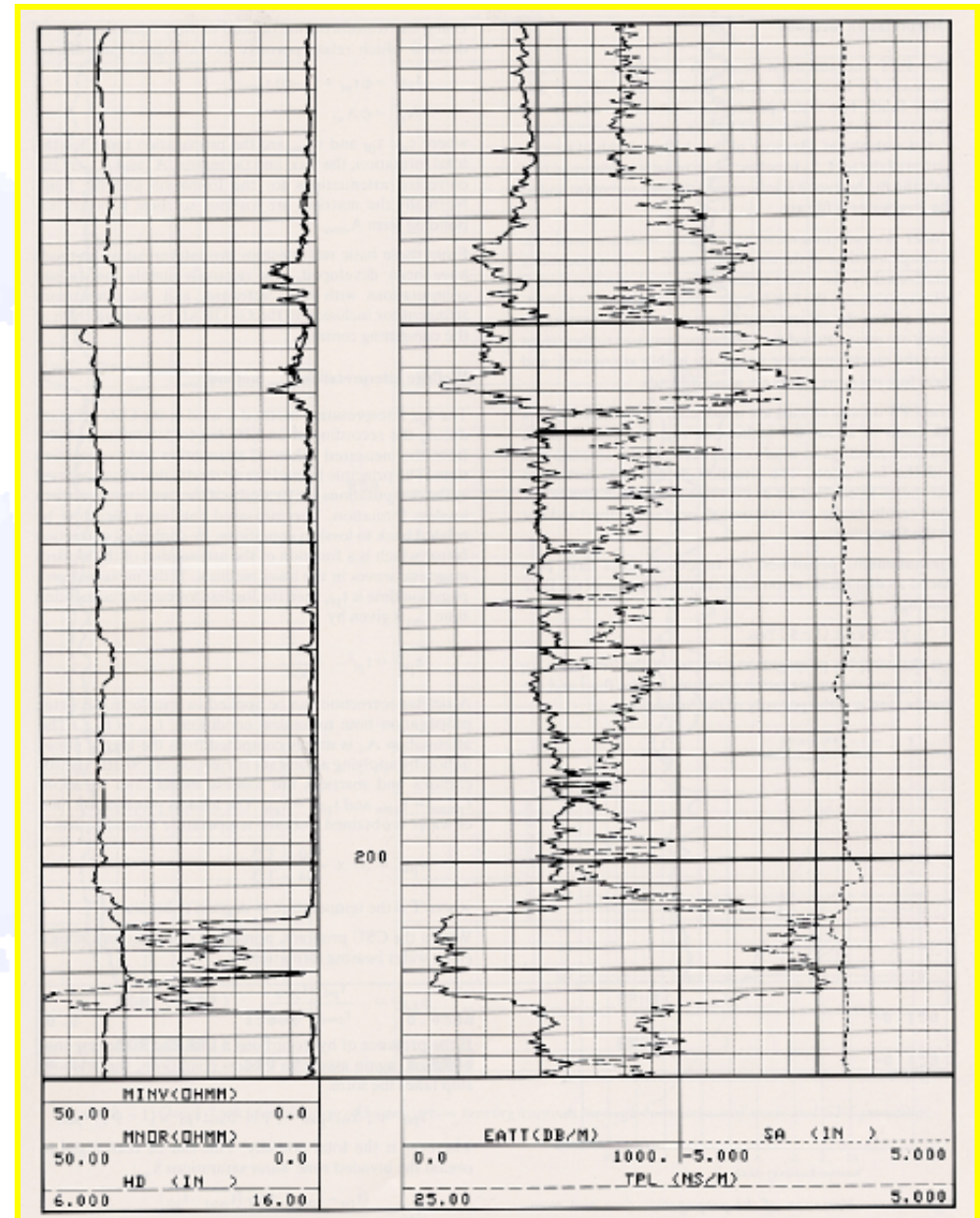
Figure 2. Electromagnetic propagation signals.

EPT logging

Table 9-1

Relative dielectric constants and propagation times for common minerals and fluids.

Mineral	Relative Dielectric Constant	Propagation Time $t_{pl}(ns/m)$
Sandstone	4.65	7.2
Dolomite	6.8	8.7
Limestone	7.5-9.2	9.1-10.2
Anhydrite	6.35	8.4
Halite	5.6-6.35	7.9-8.4
Gypsum	4.16	6.8
Dry colloids	5.76	8
Shale	5-25	7.45-16.6
Oil	2-2.4	4.7-5.2
Gas	1	3.3
Water	56-80	25-30
Fresh water	78.3	29.5



To derive FLUIDS:

- SP
- **Resistivity**
- Nuclear Magnetic Resonance (NMR)

Resistivity Logs

- The **resistivity** of a formation is a key parameter in determining hydrocarbon saturation
- The resistivity of a formation depends on:
 - Resistivity of the formation water (electricity can flow through a formation only because of the conductive water it contains)
 - Amount of water present
 - Pores structure geometry

Measuring Resistivity

- **Ohm** law defines the flux of current as:

$V = r I$ V =differential potential (volt)

r =resistance (ohm)

I =intensity of the current (ampère)

- **Resistivity** of a medium is the resistance to the flux of current measured between two opposite faces of a cube (1 meter length):

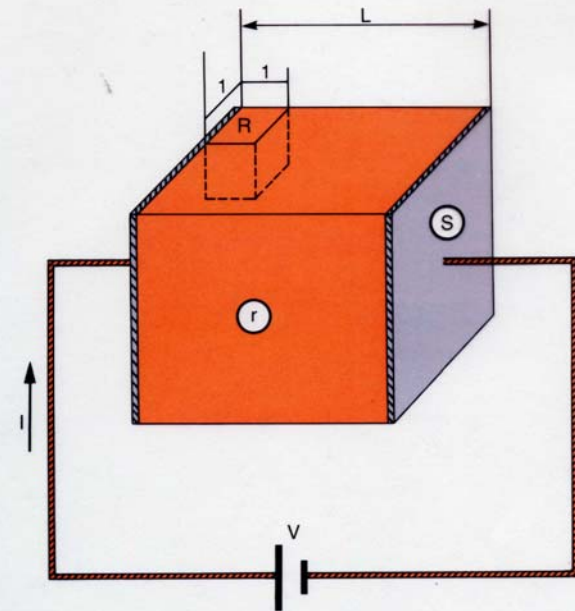
$R = r S / L$ R =resistivity (ohm.m)

r =resistance (ohm)

L =length of the cube (m)

S =surface area face of the cube (m²)

Basics of Resistivity



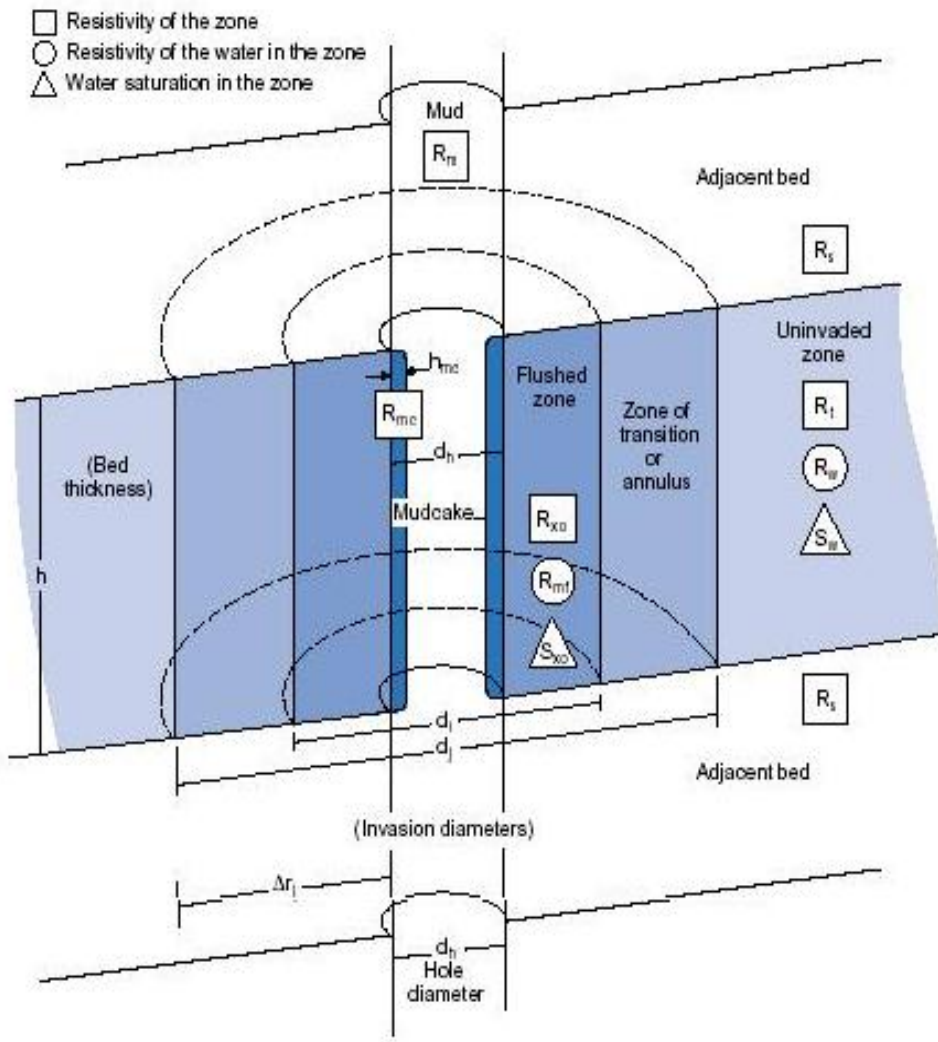
$$V = r I \quad \rightarrow \quad R = \frac{S}{L} \frac{V}{I}$$
$$r = R \frac{L}{S}$$

$$R = K \frac{V}{I}$$

Resistivity Logs

- Related to the depth of investigation
 - Macro-devices to measure R_t
 - Micro-devices to measure R_{xo}
- Related to the tool physics
 - Not focused electrode tools (WLL)
 - Focused electrode tools (WLL e LWD)
 - Low frequency induction tools (WLL)
 - Propagation EM waves tools (LWD)

Symbols Used in Log Interpretation

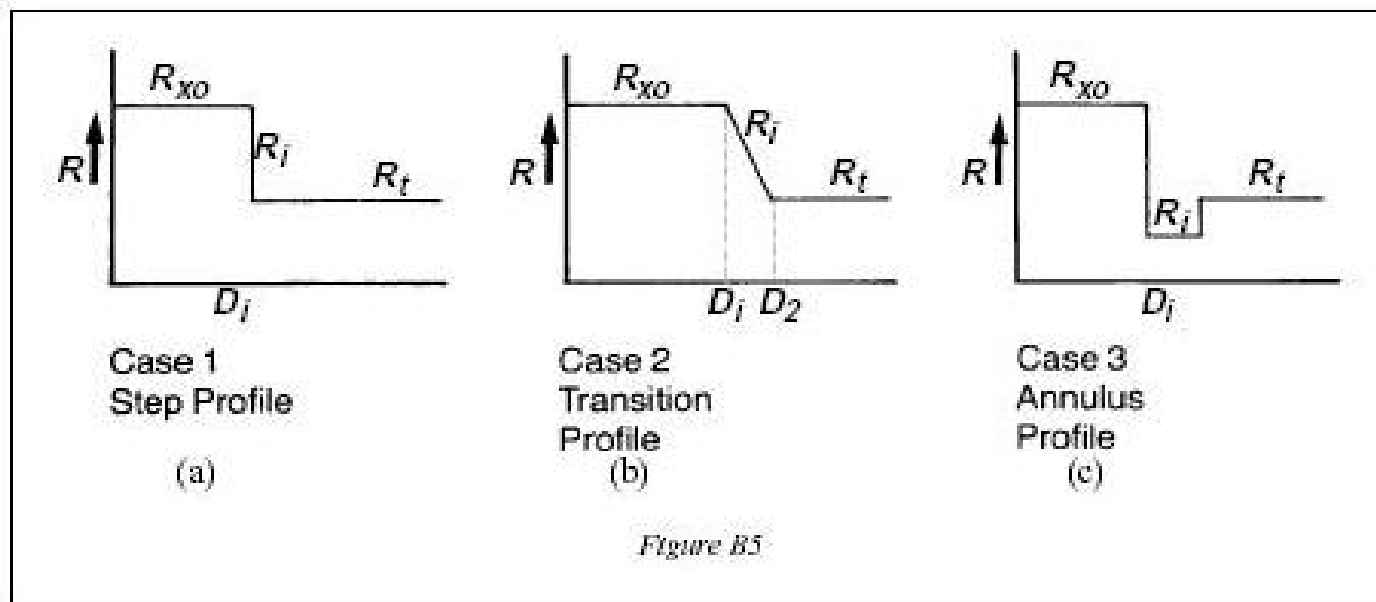
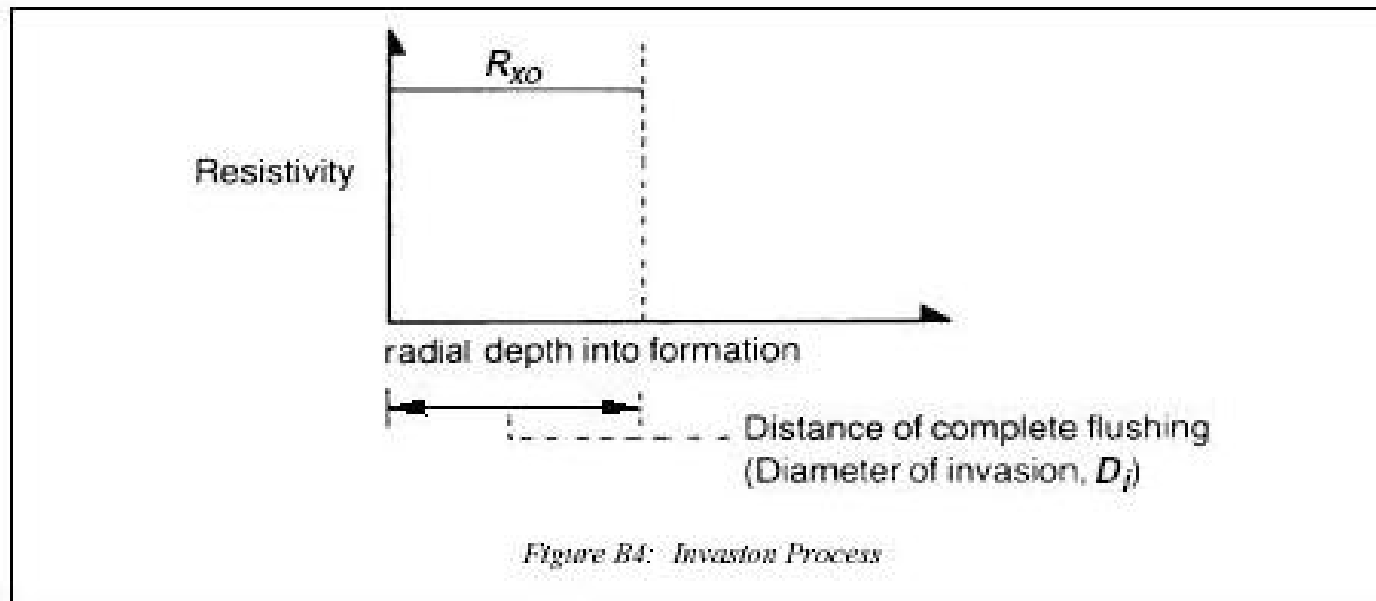


Close to the borehole formation water and some of the hydrocarbon may be flushed away by mud filtrate (flushed zone, R_{xo})

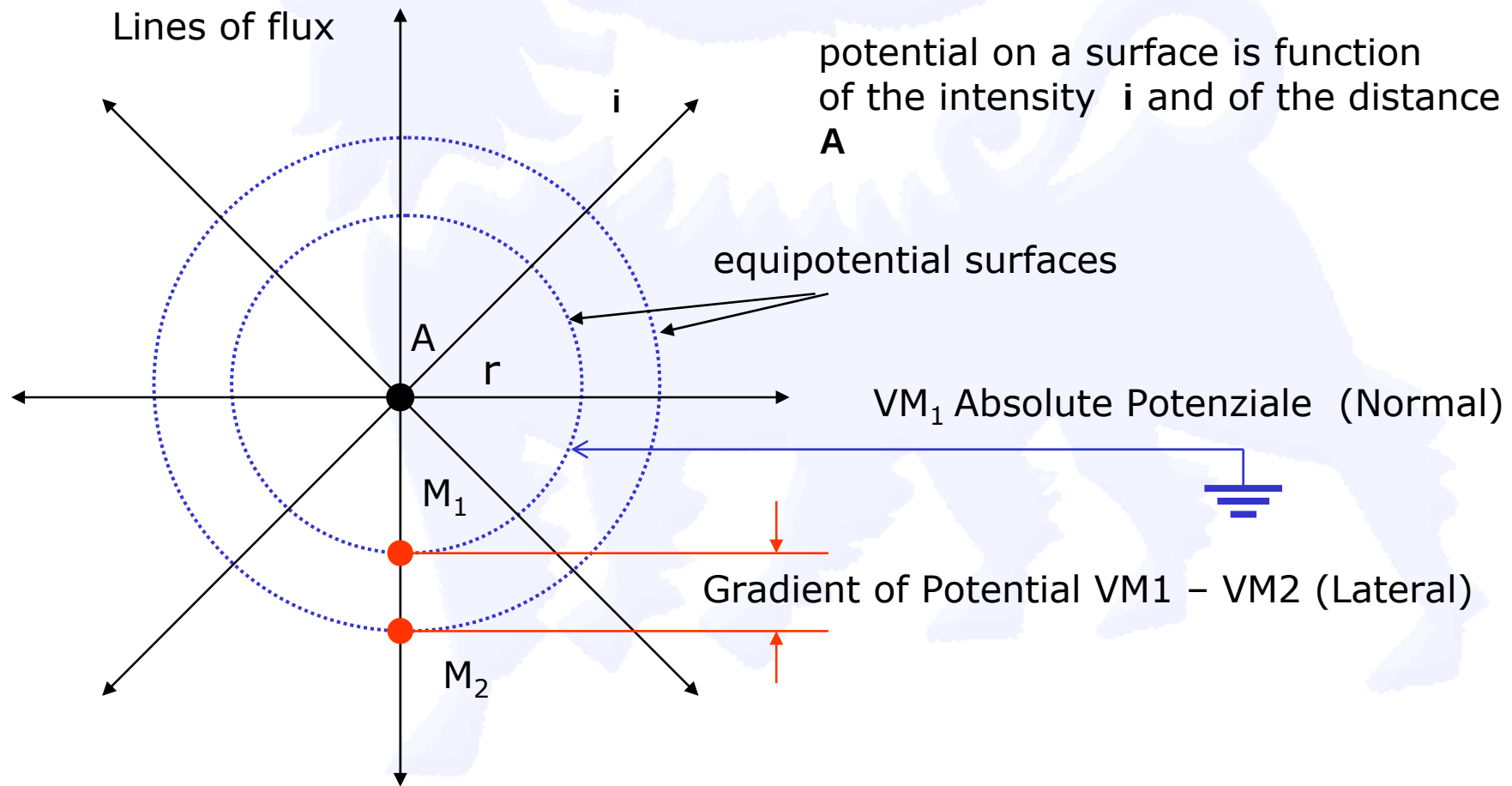
Further out, the displacement of the formation fluids by the mud filtrate is less complete, resulting in a transition from mud filtrate saturation to original formation water saturation (invaded zone)

The undisturbed formation beyond the transition zone is referred to as the non-invaded or virgin zone (R_t)

The correct estimation of the extent of the mud filtrate invasion is paramount for the correct estimation of S_w



Resistivity by galvanic sensors into isotropic medium



Not focused electrode resistivity tools

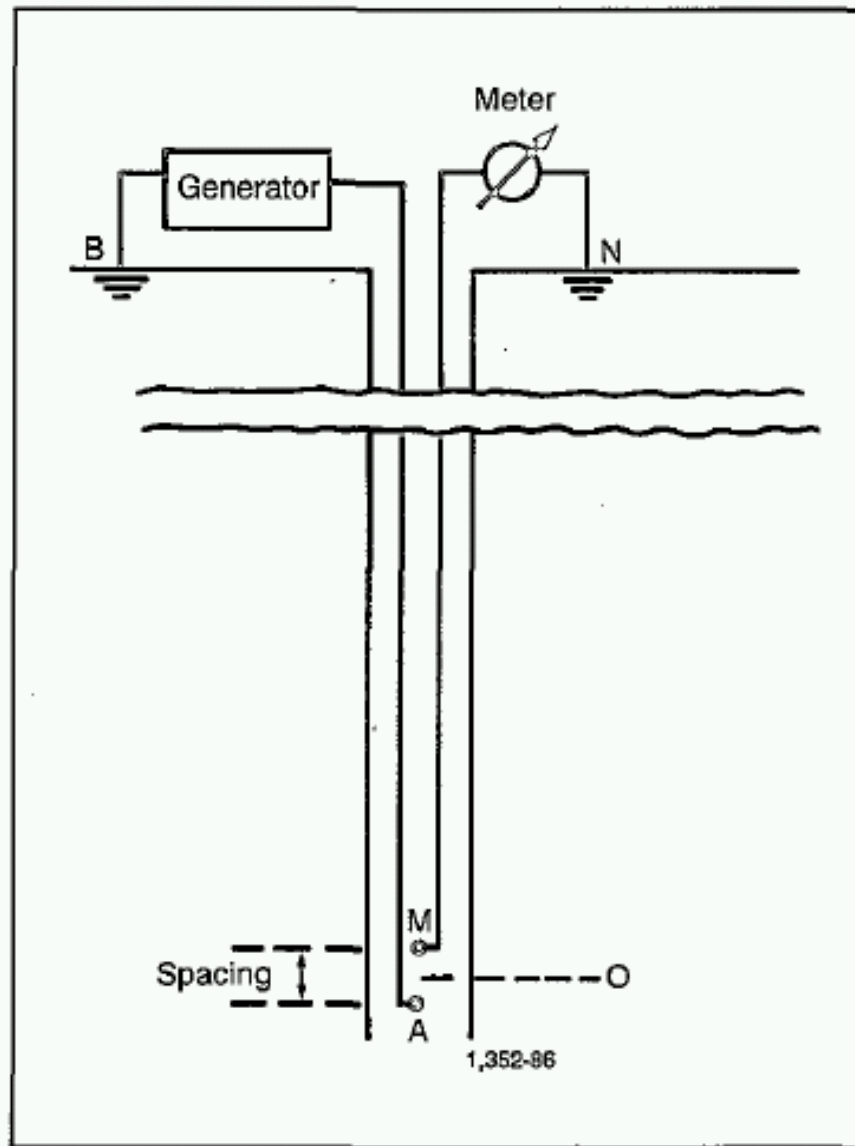


Fig. 7-1—Normal device—basic arrangement.

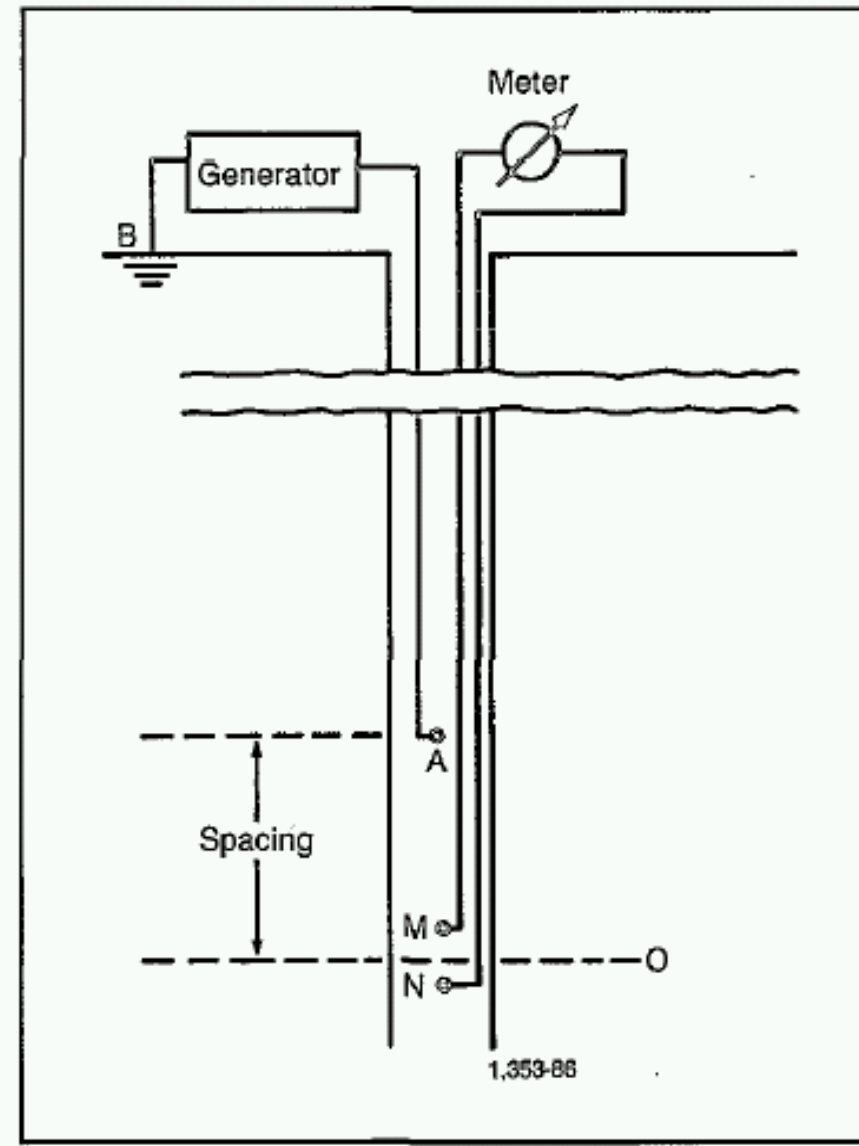


Fig. 7-2—Lateral device—basic arrangement.

Induction Tool

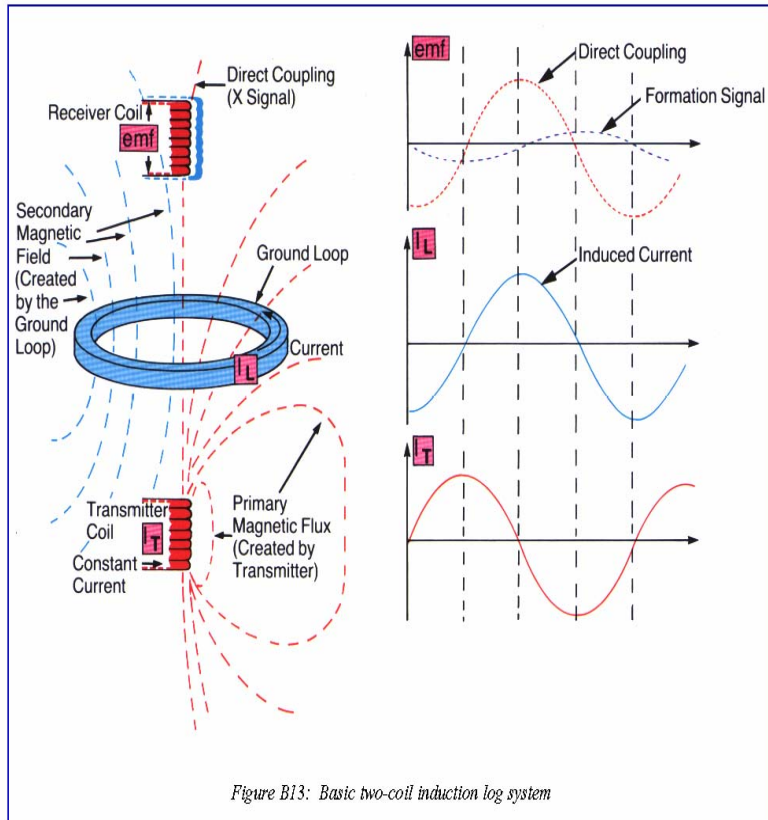
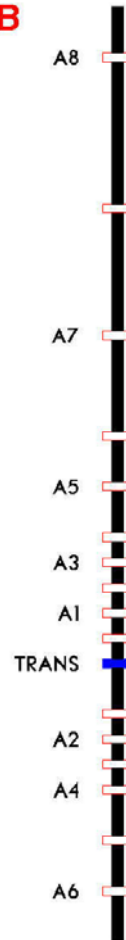
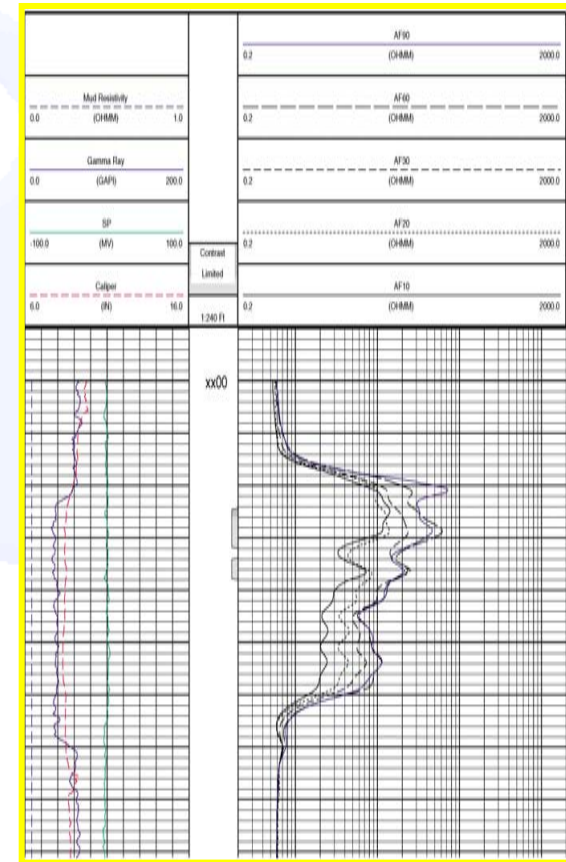
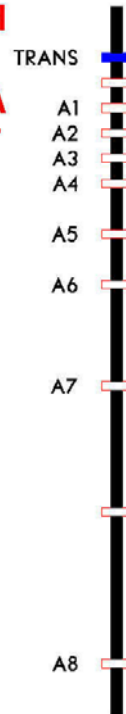


Figure B13: Basic two-coil induction log system

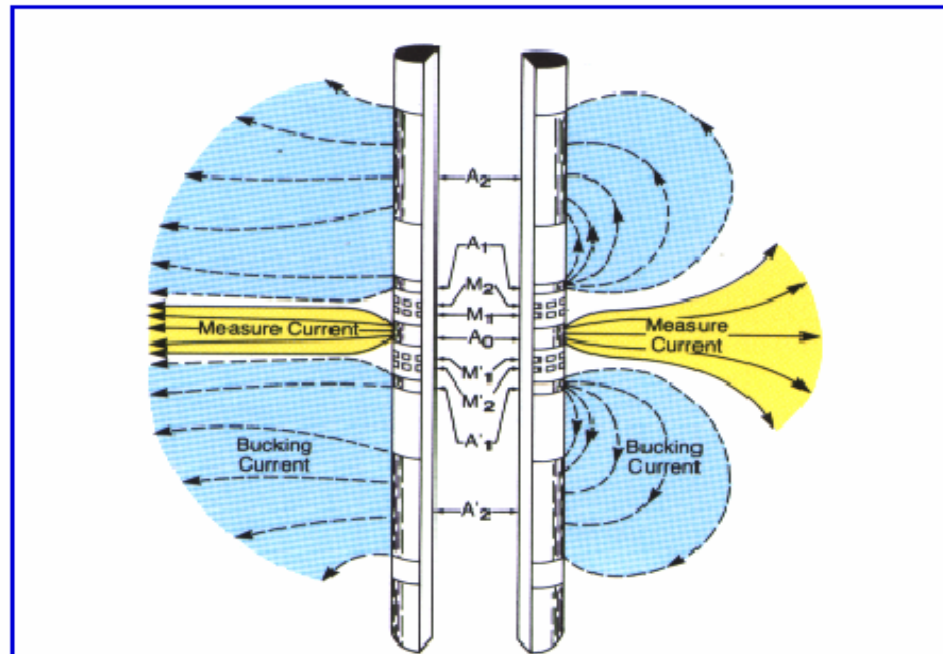
AIT-B



AIT-H
SAIT
HIT-A
QAIT

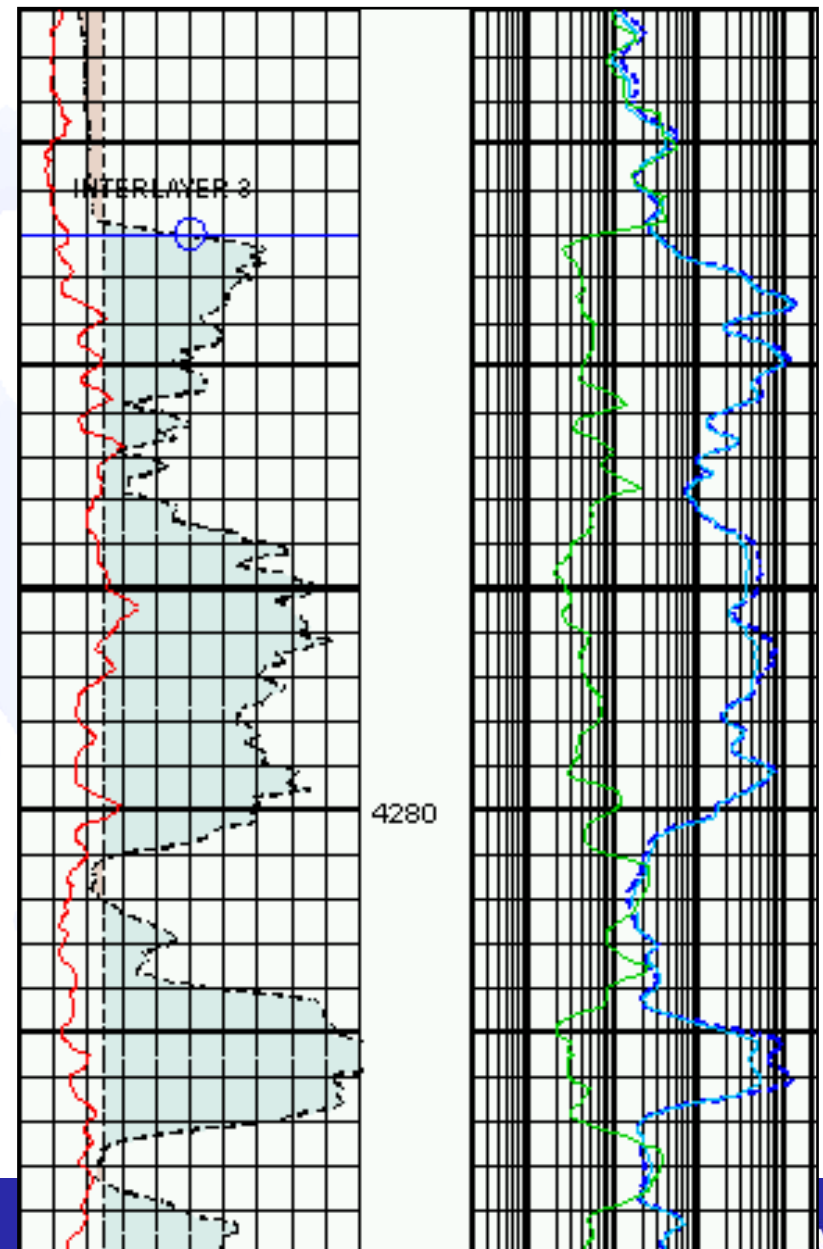


Laterolog tool



ILD		LLS	
A ₀	Measure Current Electrode	A ₀	Measure Current Electrode
M ₁ M ₂	Monitoring Electrode	M ₁ M ₂	Monitoring Electrode
A ₁	Bucking Current Electrode	A ₁	Bucking Current Emitting Electrode
A ₂	Bucking Current Electrode	A ₂	Bucking Current Return Electrode

*Figure B21: Dual Laterolog
Deep and Shallow Current Patterns*



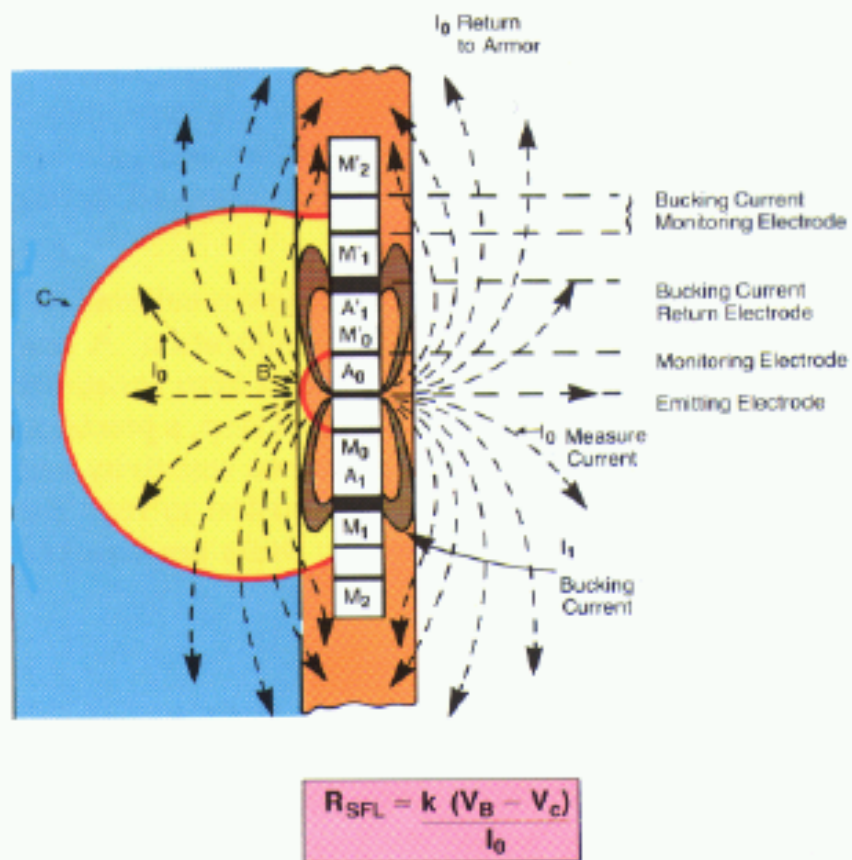
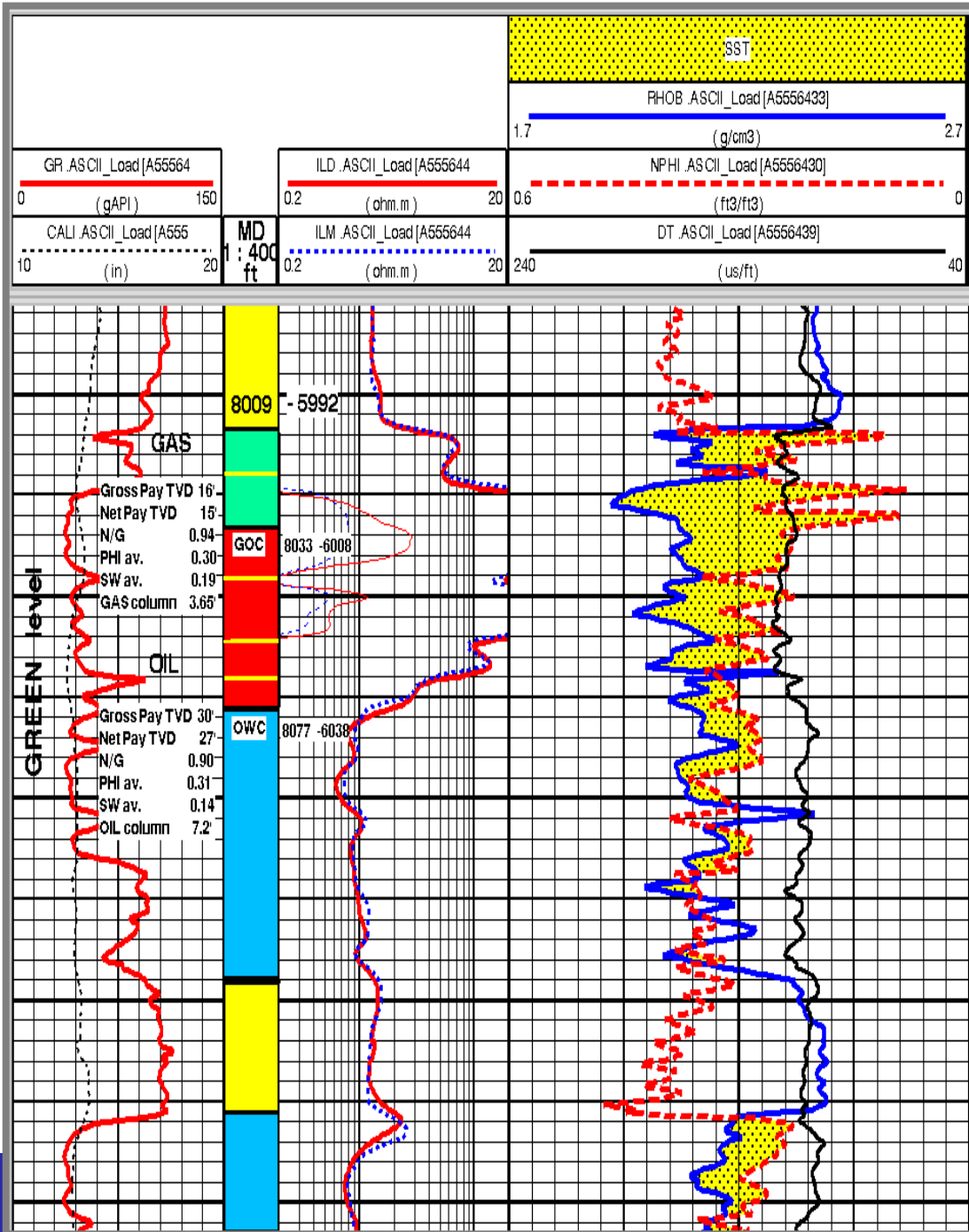


Figure B14: Electrode array of SFL tool and schematic representation of surveying current (i_0) lines (dashed) and focusing current (i_0) lines (solid).

Spherically Focused Log



Resistivity in clastic formations



Eni's Way

Microresistivity

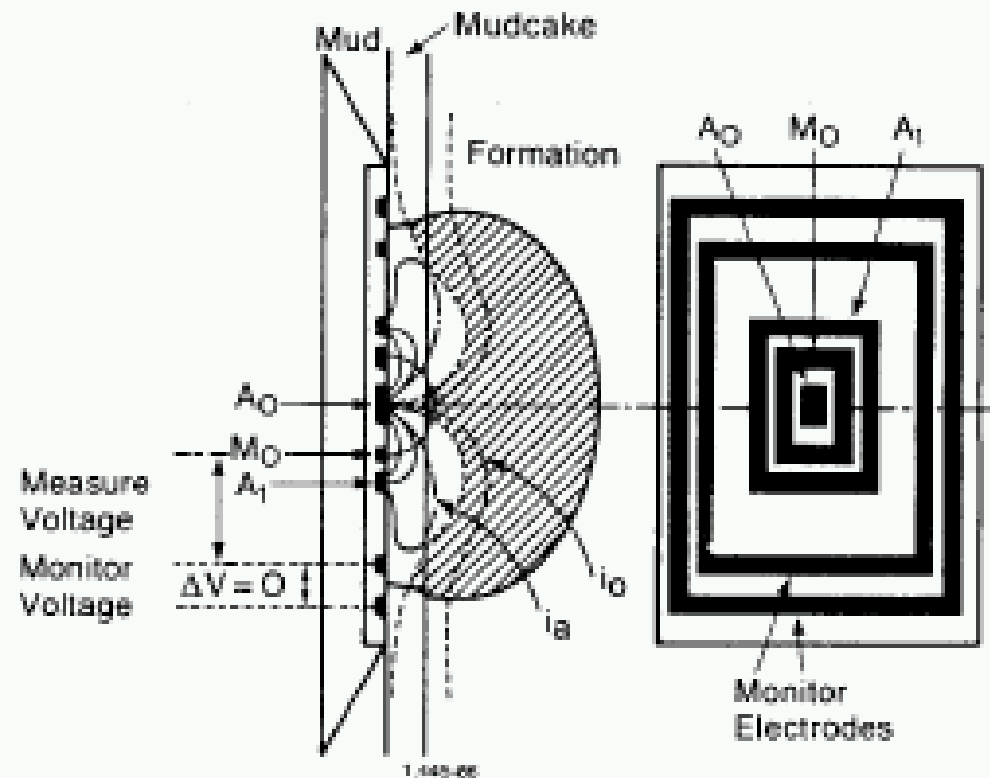
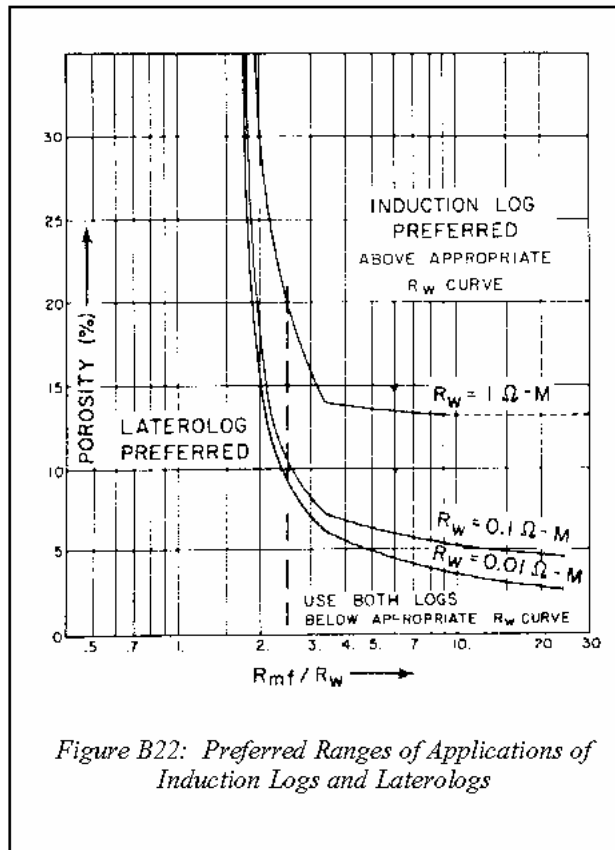


Figure B28: Current Distribution of MicroSFL device (left) and Electrode Arrangement (right)

How do we choose the fit-for-purpose resistivity tool?



- Mud properties
 - Oil Base Mud
 - Fresh Water Mud
- Formation resistivity (R_t / R_w)
- Tool characteristics
 - Induction vs galvanic

Depth of investigation: from 10 to 120 inches
Vertical resolution: from 4 to 2 ft

Resistivity logs must be corrected for borehole effects

Environmental Effects on Resistivity

- Thin layers
- Shoulder effects
- Anomalous invasion profiles
- Incoherent measurements
 - Inductive, galvanic
 - Dual tools, array tools
 - Two logging companies
- Different mud systems
 - Water base mud
 - Oil base mud

A catalogue of resistivity problems

Environmental Effects Corrections

- To recover the correct R_t value from the logged curves (R_a) we must apply the necessary environmental corrections.
- This operation is performed by using graphical charts in case of manual qualitative interpretation, but it is very difficult and complex in case of quantitative interpretation of digital data.
- In this case the only feasible solution is the use of an **automatic modelling & inversion technique**.

Modelling & Inversion

- Modelling & Inversion is a two-step interactive process:
- **Modelling Step**: design a parametric model of subsurface in the proximity of the borehole (the formation) and compute the corresponding tool response (synthetic logs);
 - Formation model (geometry & petrophysics)
 - Tool numerical forward model
- **Inversion Step**: adjust formation parameters to fit measured data (resistivity logs),
 - Log matching
 - Optimisation

Porosity Logs

POROSITY (Φ), defines the “storage” capacity of a reservoir.

The following logs are used to evaluate the porosity:

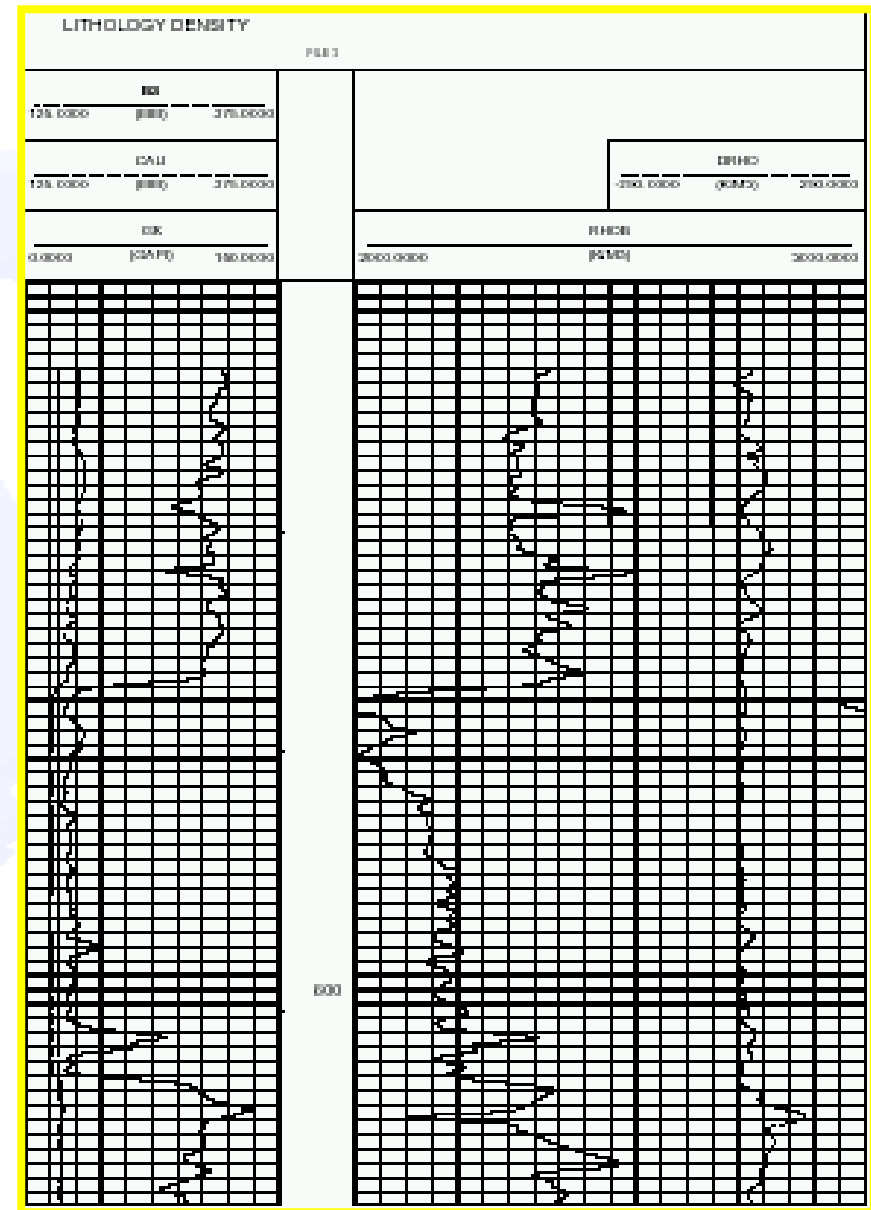
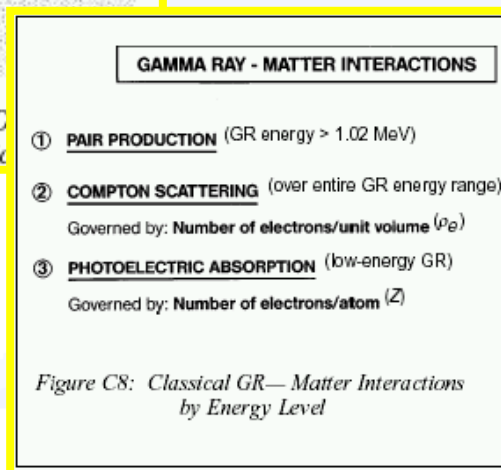
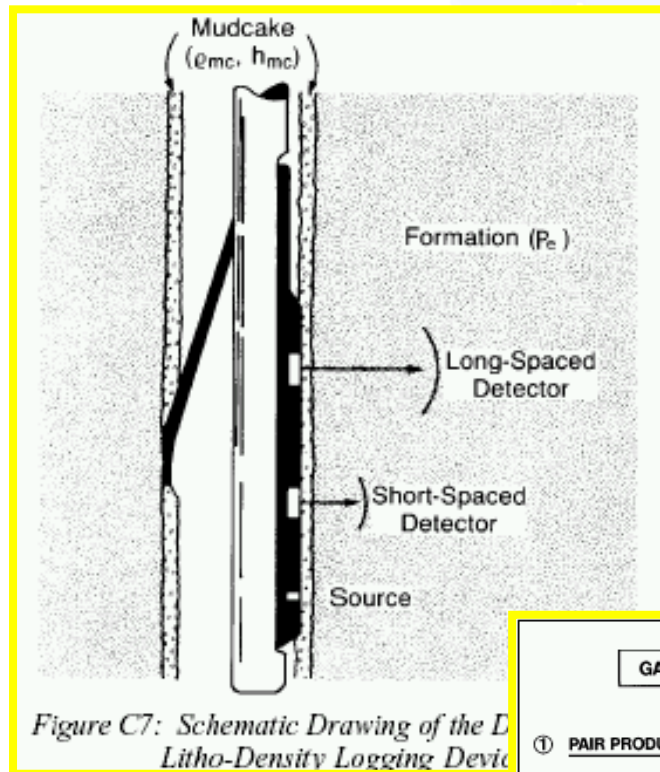
- **DENSITY**
- **NEUTRON**
- **SONIC**

- **DIELECTRIC**
- **NUCLEAR MAGNETIC RESONANCE**

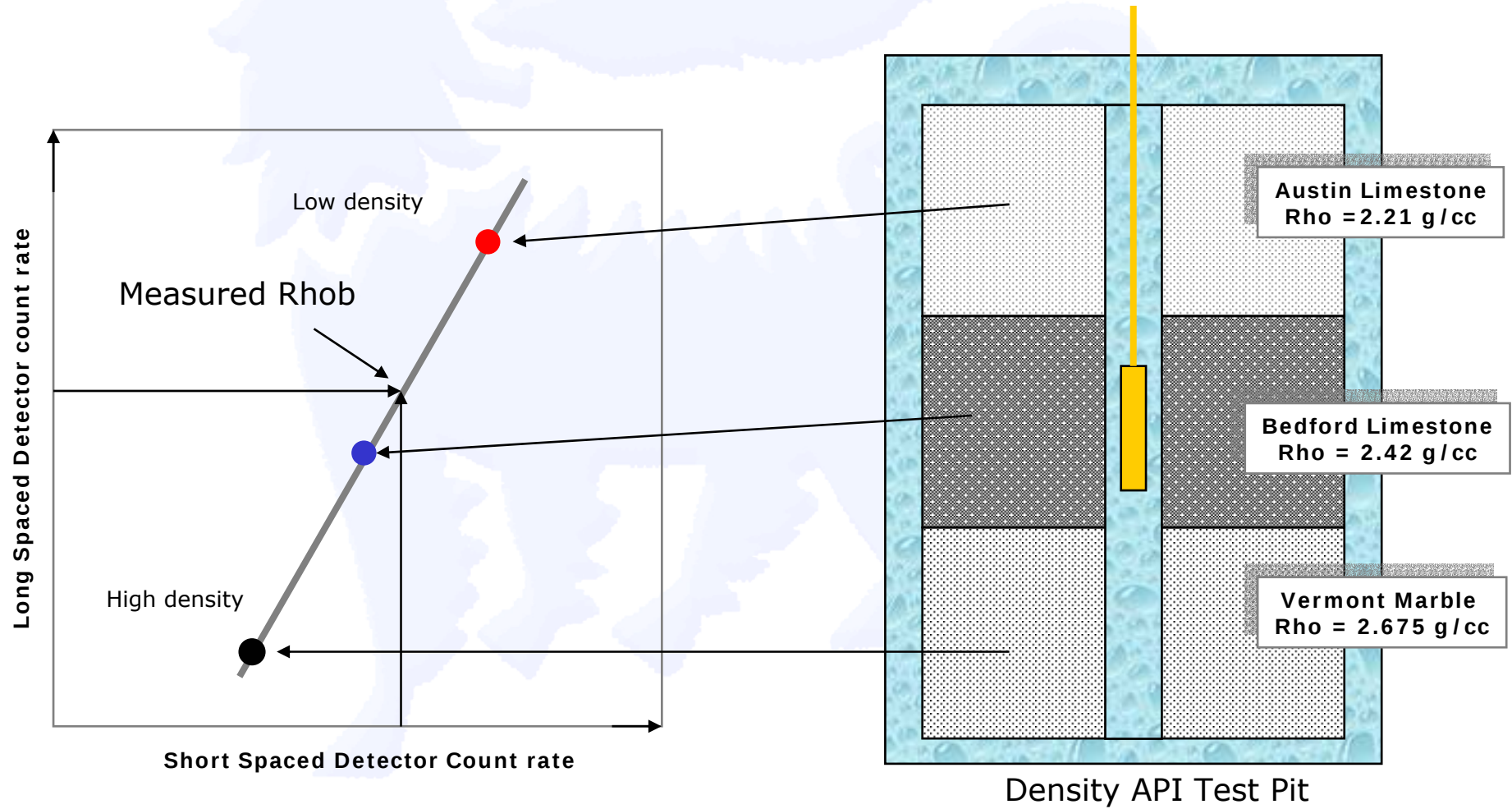
Density Log

- The **Density log** measures the bulk density (RHOB) of a formation, by means of detecting gamma rays sent by a source to the formation
- The bulk density is a function of:
 - matrix density of the rock type
 - porosity of the rock type
 - fluid density in the pores space

Density Log



CALIBRATION



POROSITY FROM DENSITY LOG

$$\rho_b = \phi \rho_f + (1 - \phi) \rho_{ma} \text{ (clean wet zone)}$$

where:

ρ_b is the measured bulk density (from Litho-Density tool)

ρ_{ma} is the density of the matrix

ρ_f is the density of the fluid

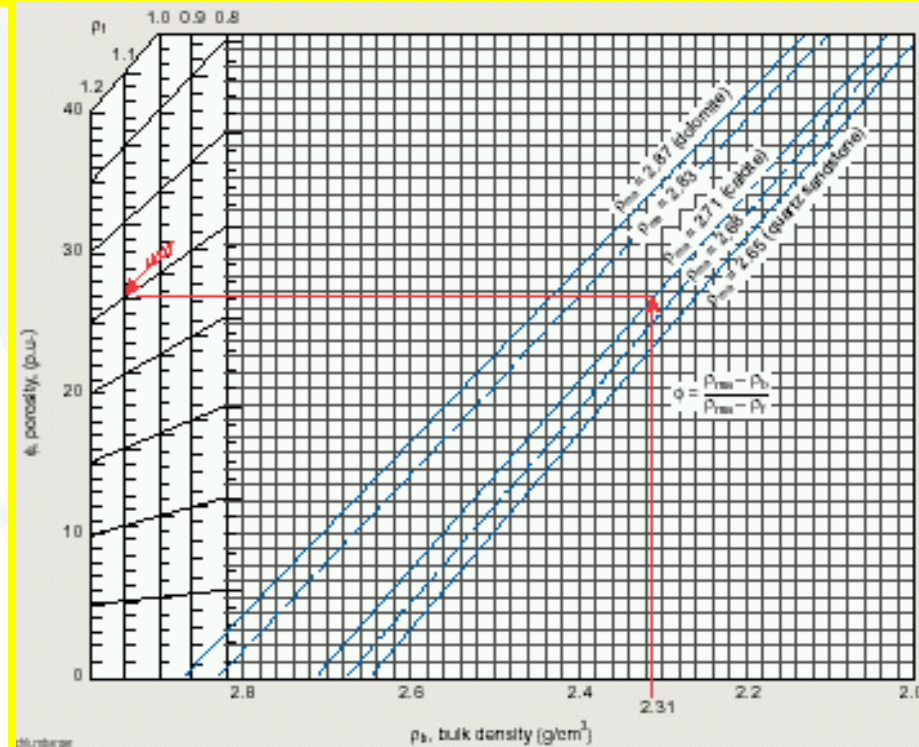
ϕ is the percent volume of pore space

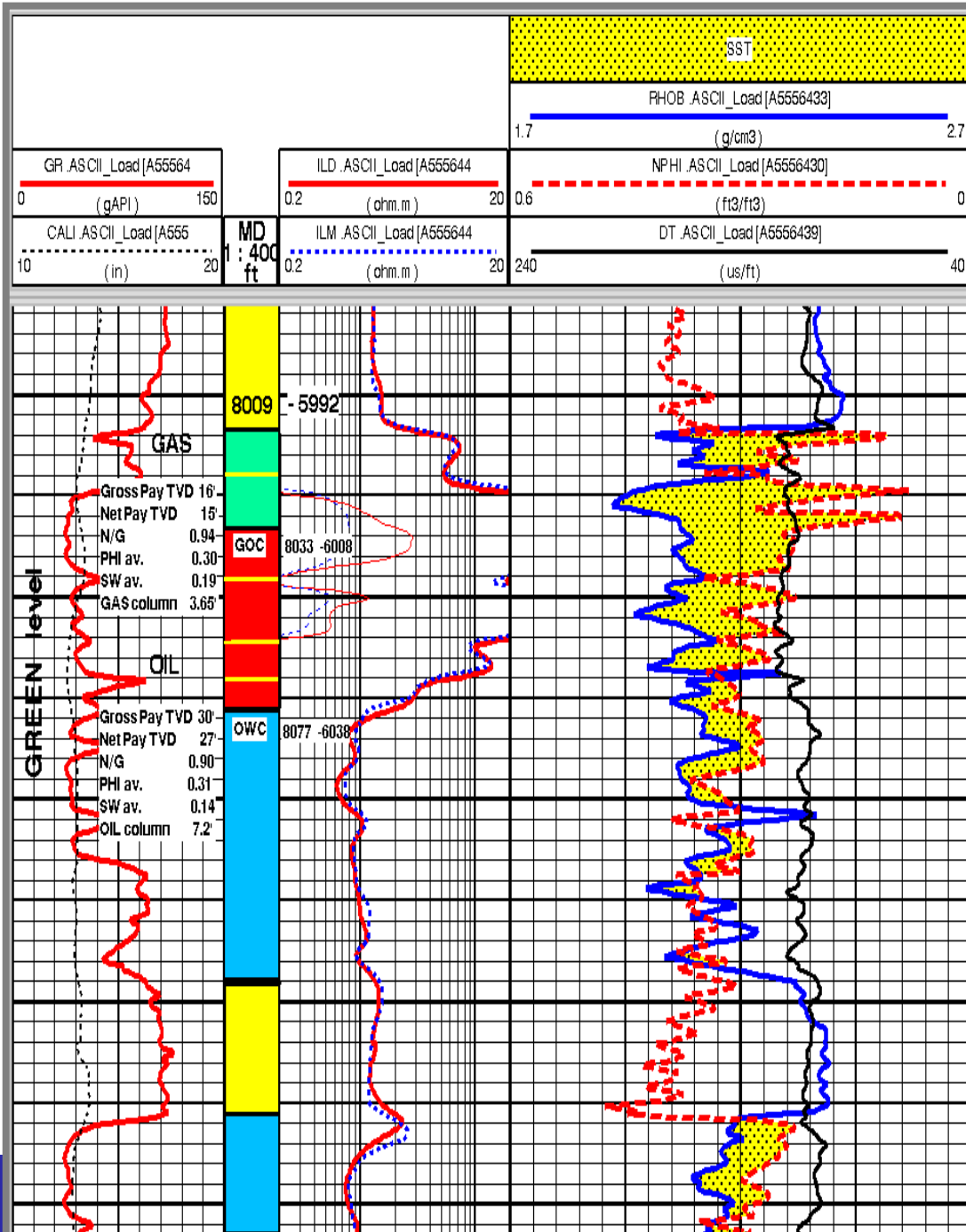
$(1 - \phi)$ is the percent volume of matrix.

$$\Phi = \rho_{ma} - \rho_b / \rho_{ma} - \rho_f$$

Table 5-3

Compound	Formula	Actual Density ρ_b	$\frac{2\sum Z^2}{\text{Mol. Wt.}}$	ρ_a	ρ_a (as seen by tool)
Quartz	SiO ₂	2.654	0.9985	2.650	2.648
Calcite	CaCO ₃	2.710	0.9991	2.708	2.710
Dolomite	CaCO ₃ MgCO ₃	2.850	0.9977	2.863	2.850
Anhydrite	CaSO ₄	2.960	0.9990	2.957	2.977
Sylvite	KCl	1.984	0.9657	1.916	1.863
Halite	NaCl	2.165	0.9581	2.074	2.032
Gypsum	CaSO ₄ 2H ₂ O	2.320	1.0222	2.372	2.351
Anthracite Coal		{1.400} {1.800}	1.0300	{1.442} {1.852}	{1.355} {1.796}
Bituminous Coal		{1.200} {1.500}	1.0600	{1.272} {1.590}	{1.173} {1.514}
Fresh Water	H ₂ O	1.000	1.1101	1.110	1.000
Salt Water	200,000 ppm	1.146	1.0797	1.237	1.135
Oil	n(CH ₂)	0.850	1.1407	0.970	0.850
Methane	CH ₄	ρ_{meth}	1.2470	1.247 ρ_{meth}	1.335 ρ_{meth} - 0.188
Gas	C _{1.1} H _{4.2}	ρ_g	1.238	1.238 ρ_g	1.325 ρ_g - 0.188





Gas Effect

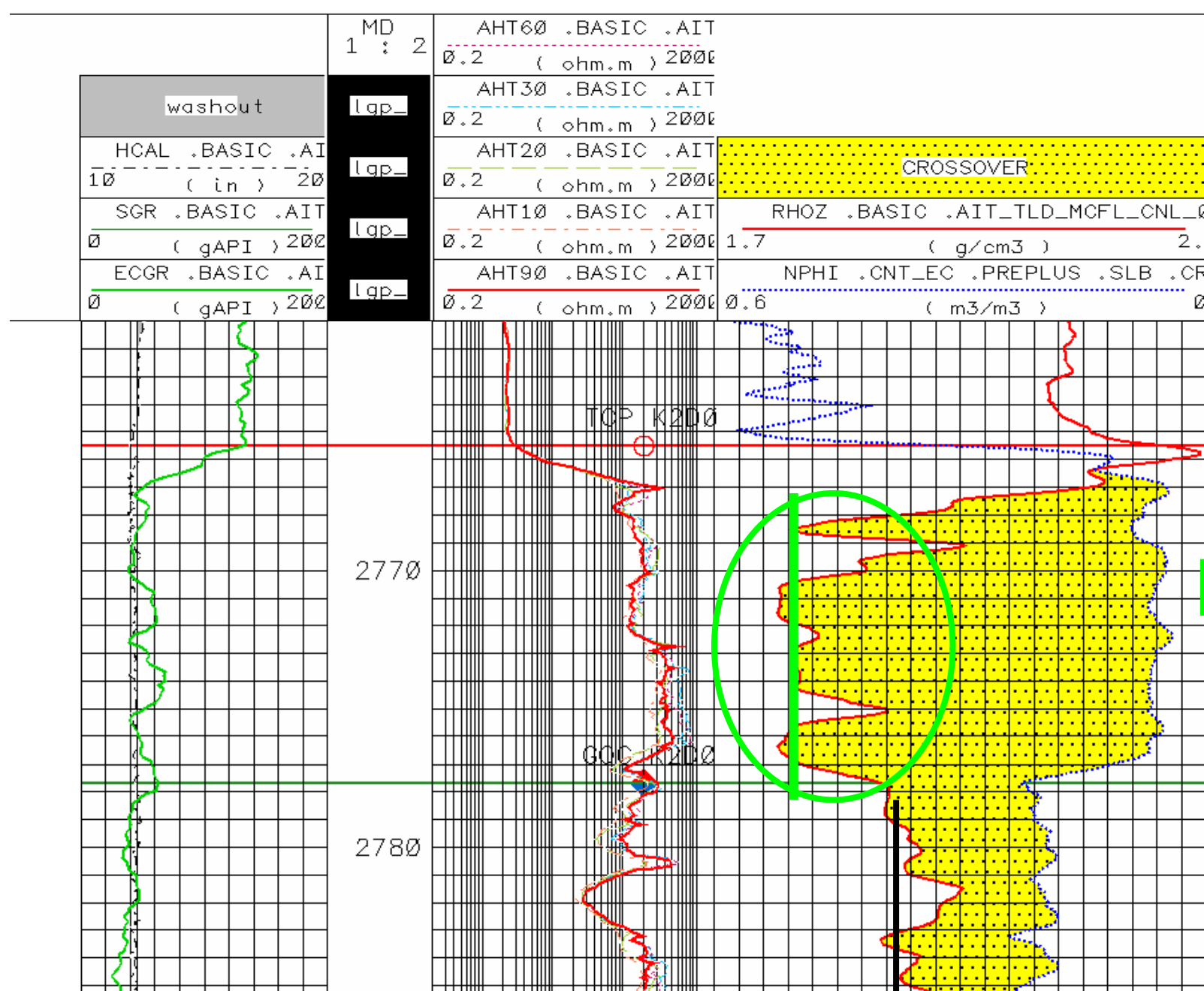
In a gas bearing formation, the measured density is lower than the theoretical density if the same formation were water bearing or oil bearing

This effect is referred to as "gas effect" and is visible on the density/neutron log combination

In a gas bearing reservoir, before computing the porosity, the RHOB log must be corrected for this effect



Eni's Way



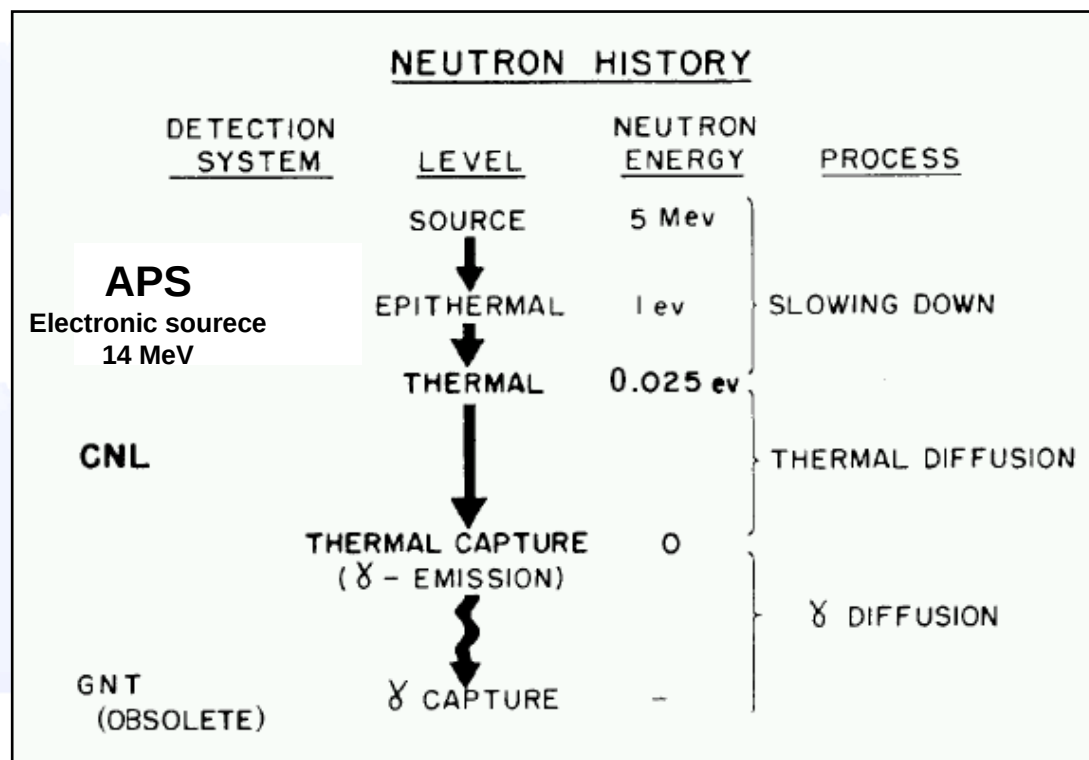
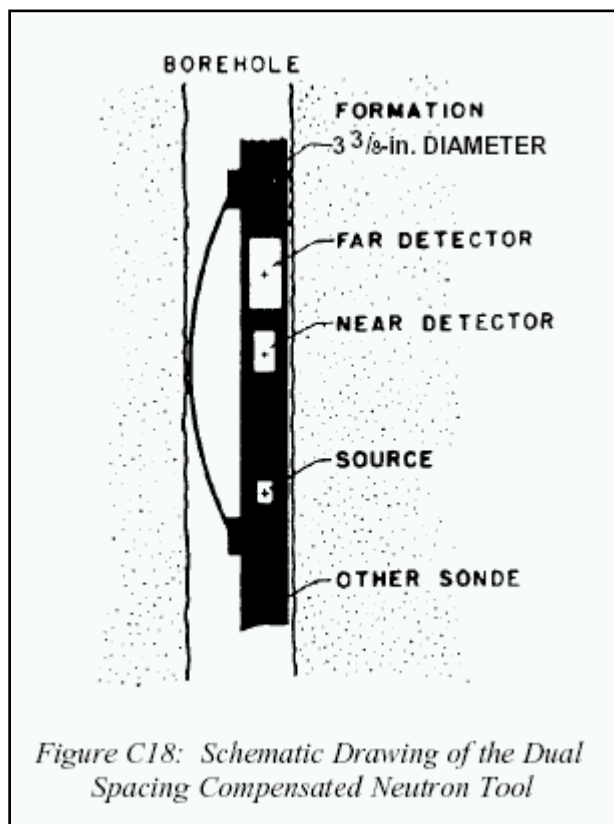
GAS effect

POROSITY (Φ), defines the “storage” capacity of a reservoir.

The following logs are used to evaluate the porosity:

- DENSITY
- **NEUTRON**
- SONIC
- DIELECTRIC
- NUCLEAR MAGNETIC RESONANCE

Neutron Log

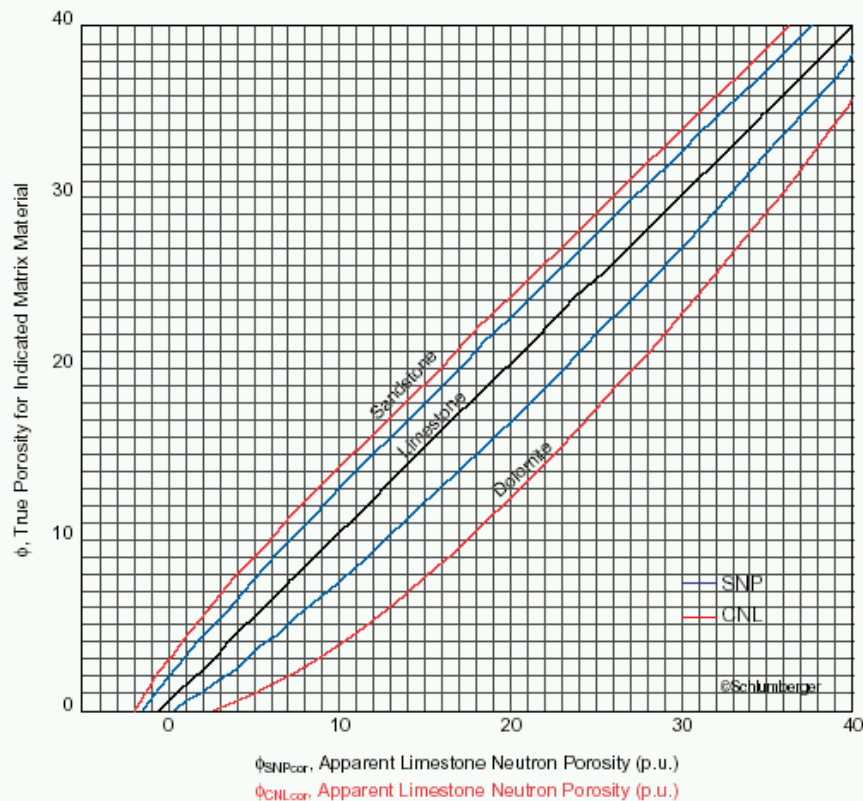


The **Neutron Log** responds essentially to the hydrogen content of the formation. In clean formations (water- or oil-bearing), this log directly measures the formation porosity

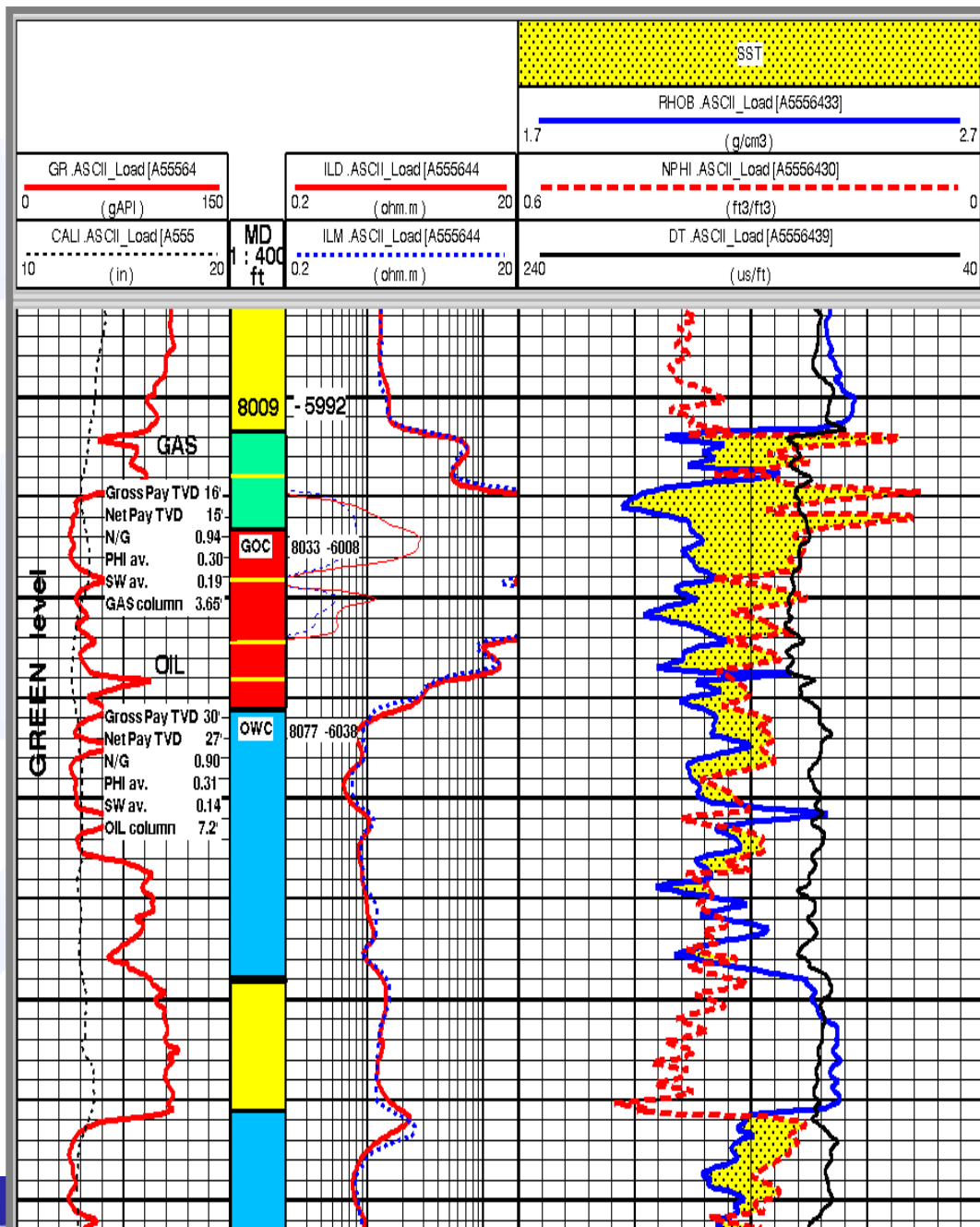
This is true if matrix density is around 2.71 g/cc (sandstone, limestone). If matrix density is different a correction is required.

Neutron Porosity Equivalence Curves

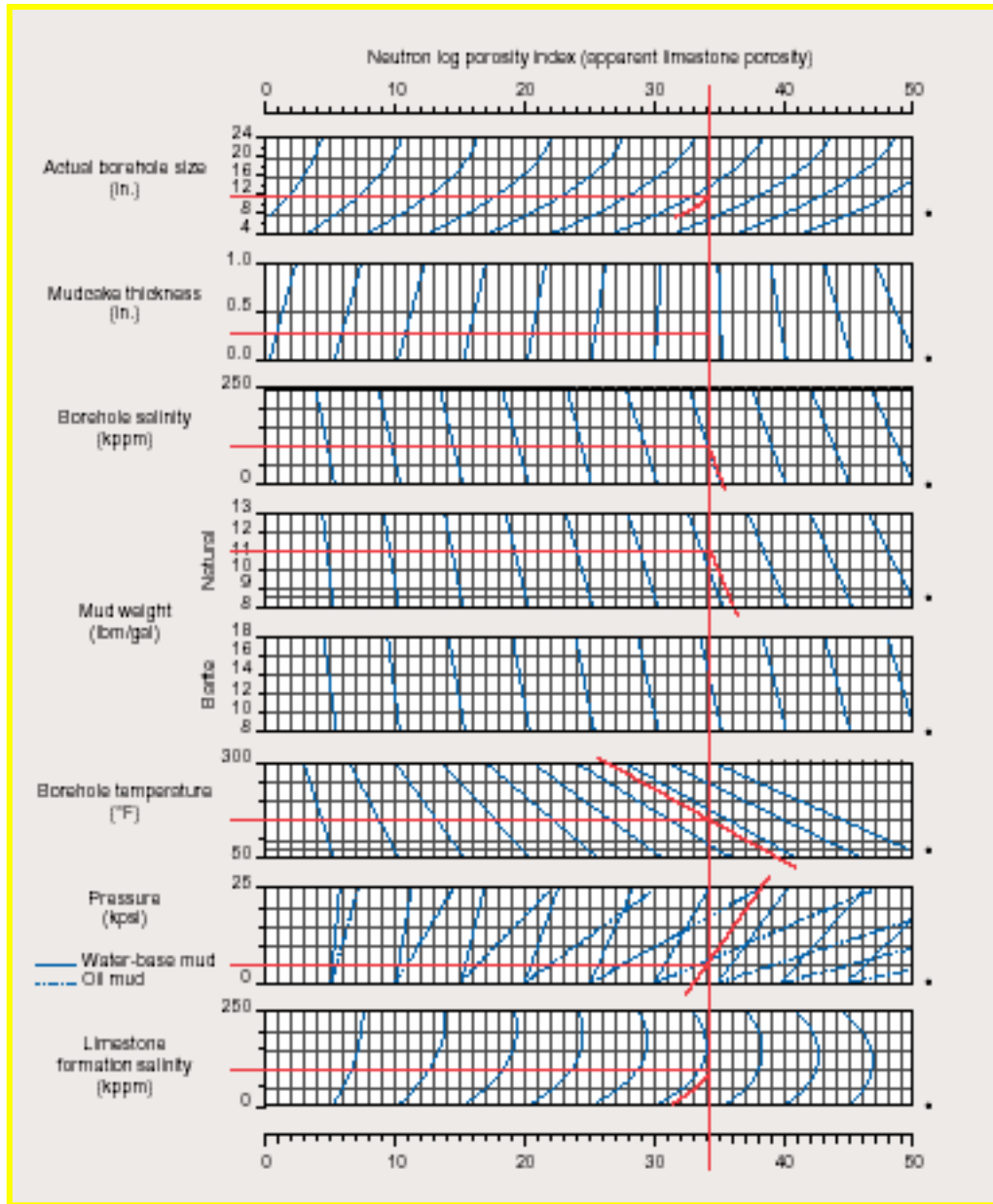
Sidewall Neutron Porosity (SNP), Compensated Neutron Log (CNL*)



Correction Chart for
Neutron Log

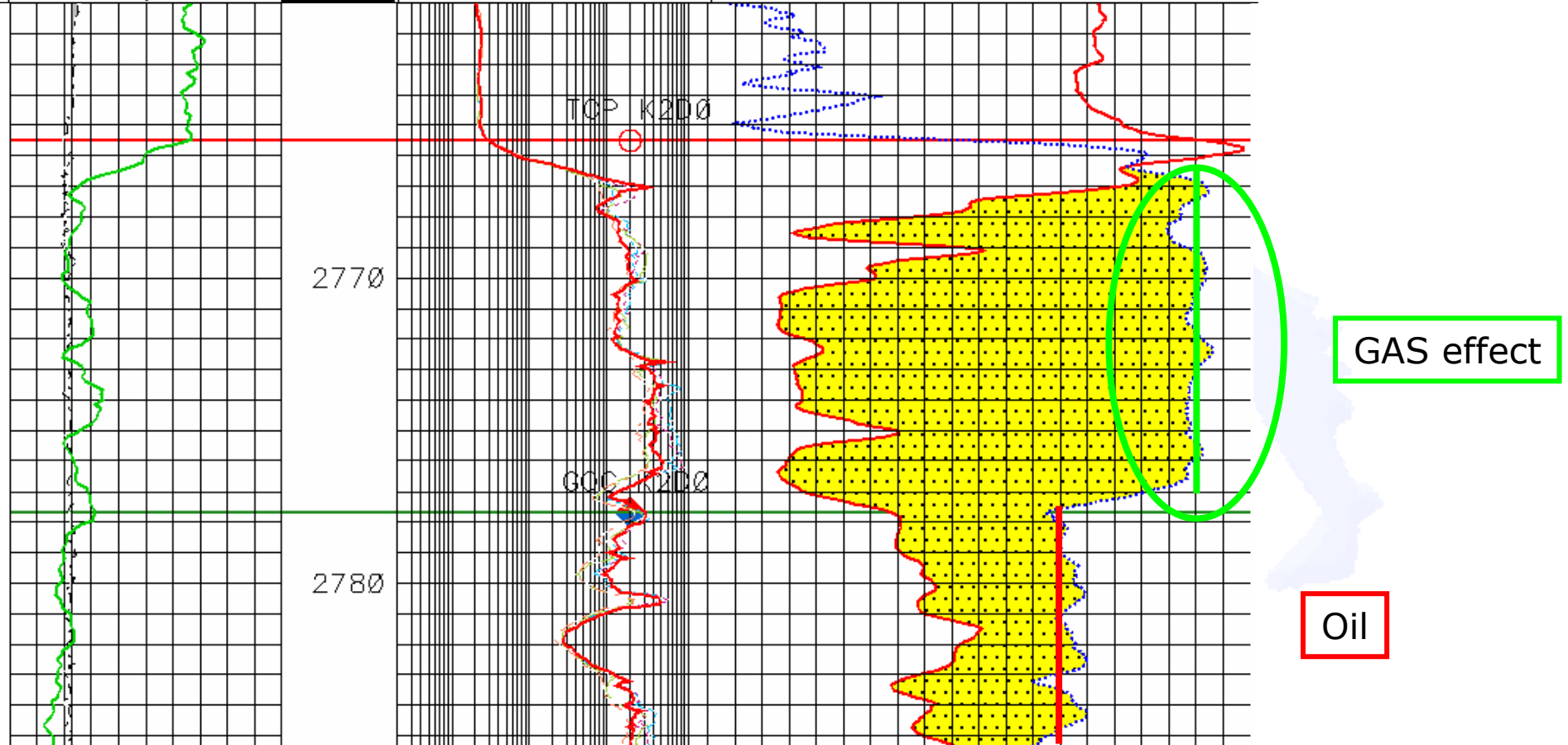


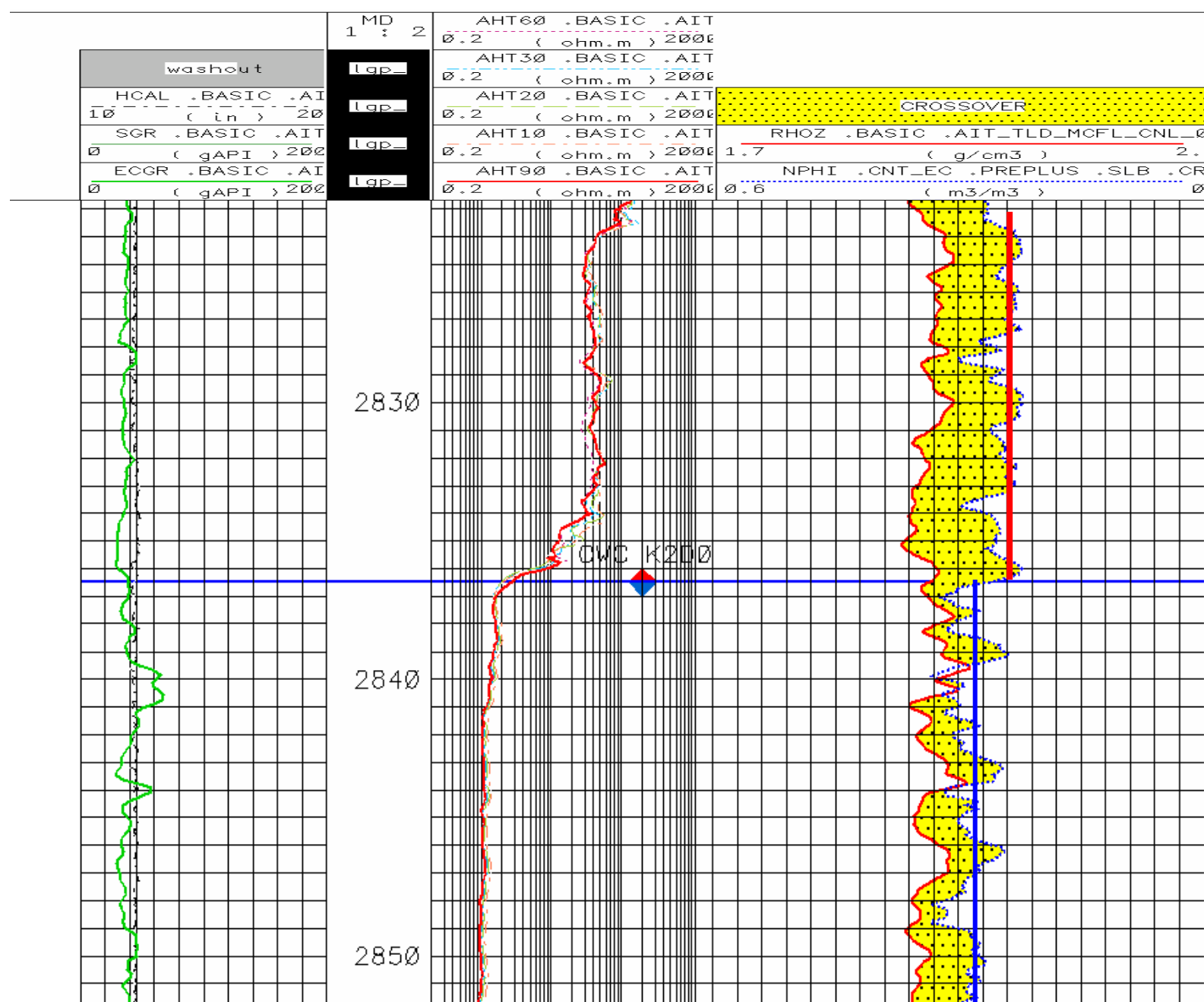
Environmental corrections for CNL (Compensated Neutron Log)



- Hole diameter
- Mud cake thickness
- Salinity
- Mud weight
- Temperature
- Pressure

	MD 1 : 2	AHT60 .BASIC .AIT 0.2 (ohm.m) 2000	
washout	lqp_	AHT30 .BASIC .AIT 0.2 (ohm.m) 2000	
HCAL .BASIC .AIT 10 (in) 20	lqp_	AHT20 .BASIC .AIT 0.2 (ohm.m) 2000	CROSSOVER
SGR .BASIC .AIT 0 (gAPI) 200	lqp_	AHT10 .BASIC .AIT 0.2 (ohm.m) 2000	RHOZ .BASIC .AIT_TLD_MCFL_CNL_0 1.7 (g/cm3) 2.
ECGR .BASIC .AIT 0 (gAPI) 200	lqp_	AHT90 .BASIC .AIT 0.2 (ohm.m) 2000	NPHI .CNT_EC .PREPLUS .SLB .CR 0.6 (m3/m3) 0

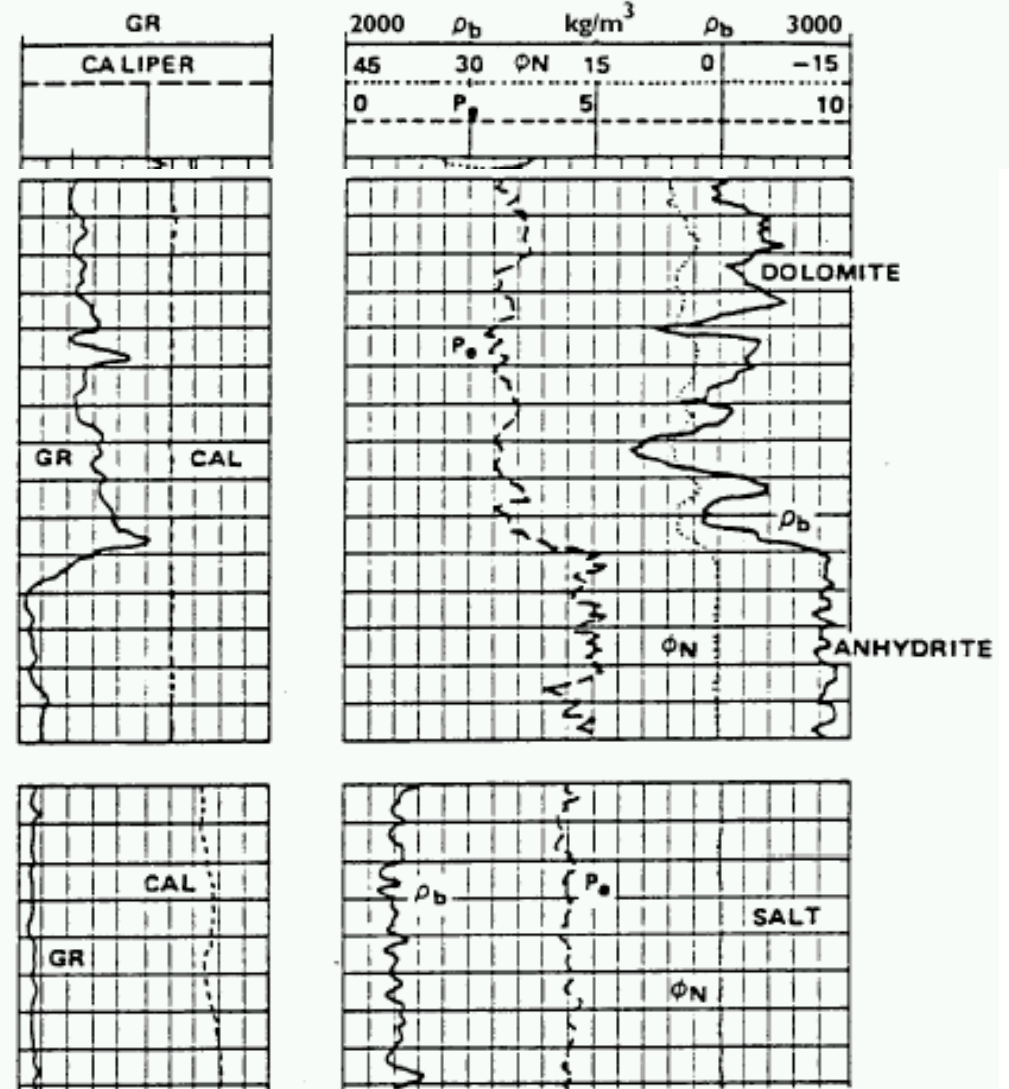
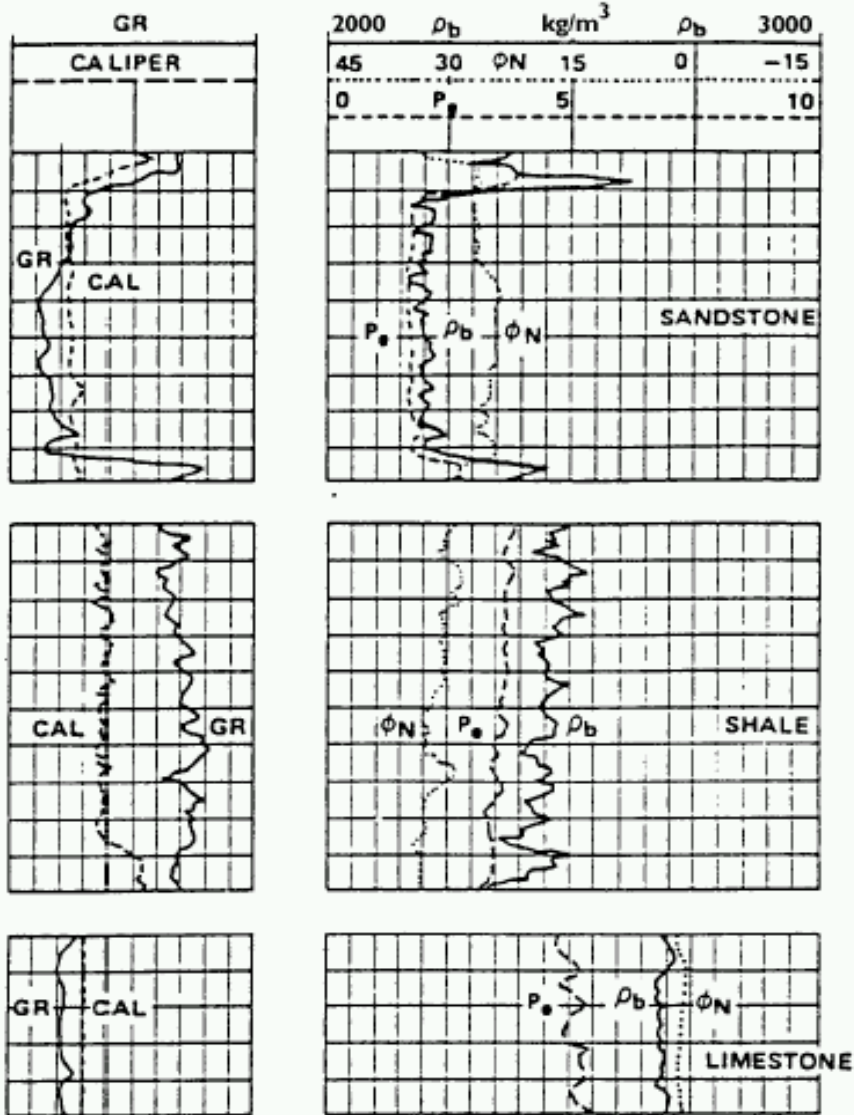


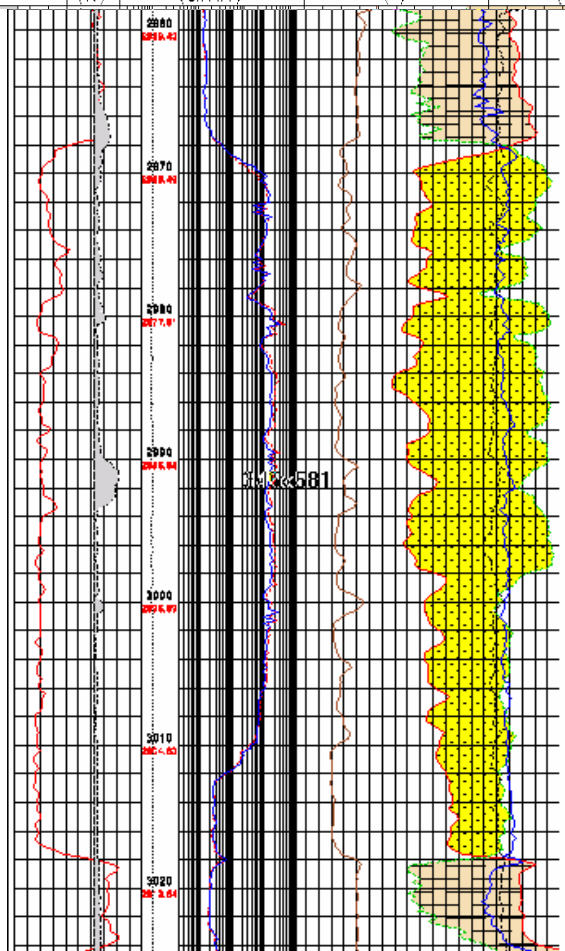
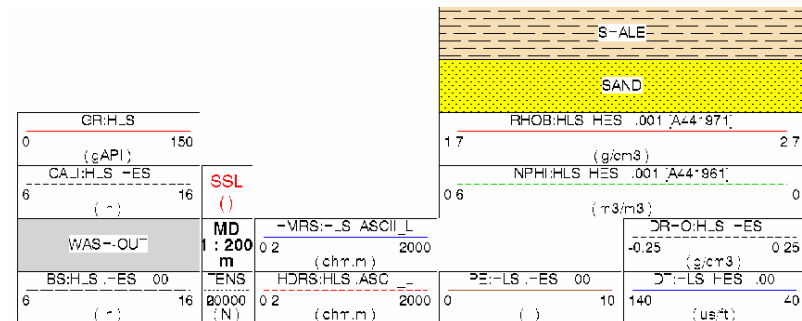


Oil

Water

Lithology from Density/Neutron combination

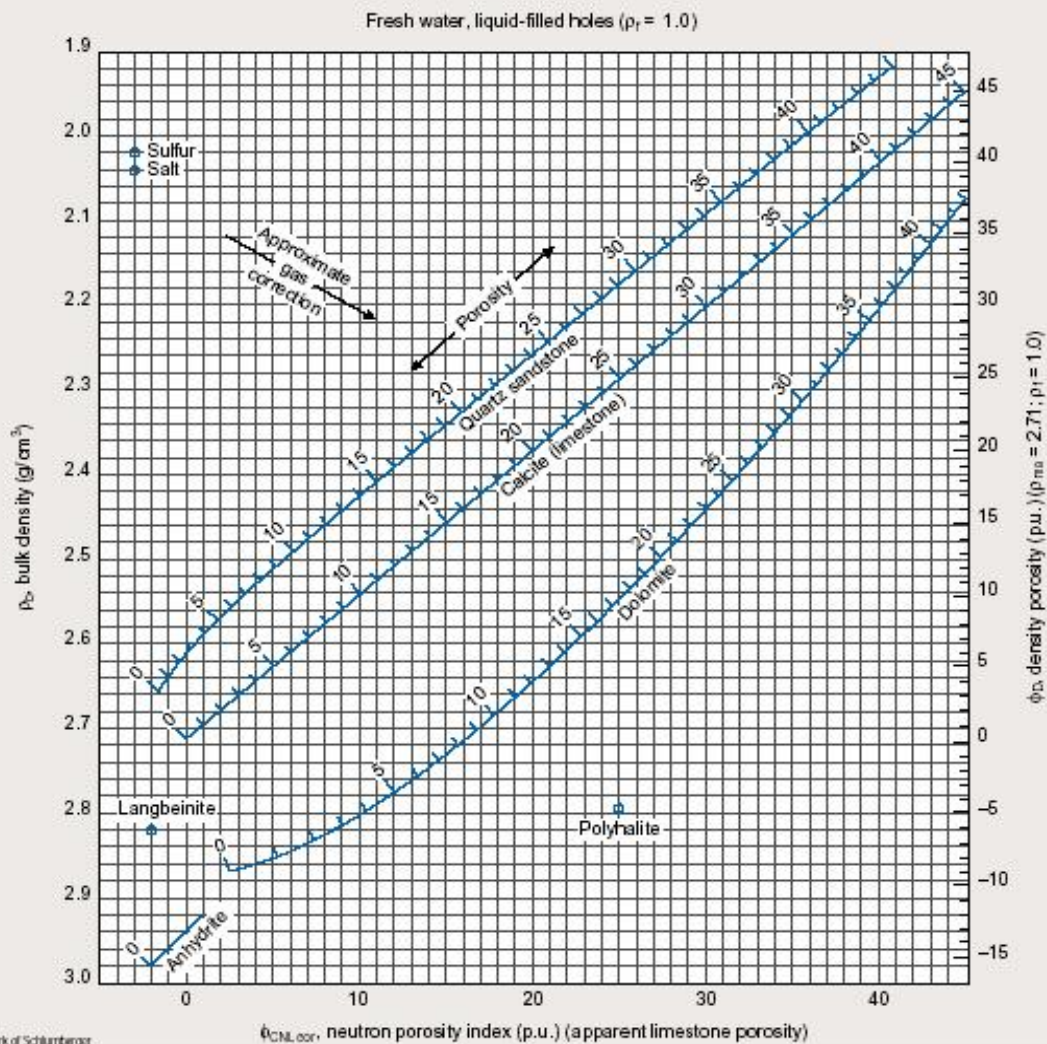




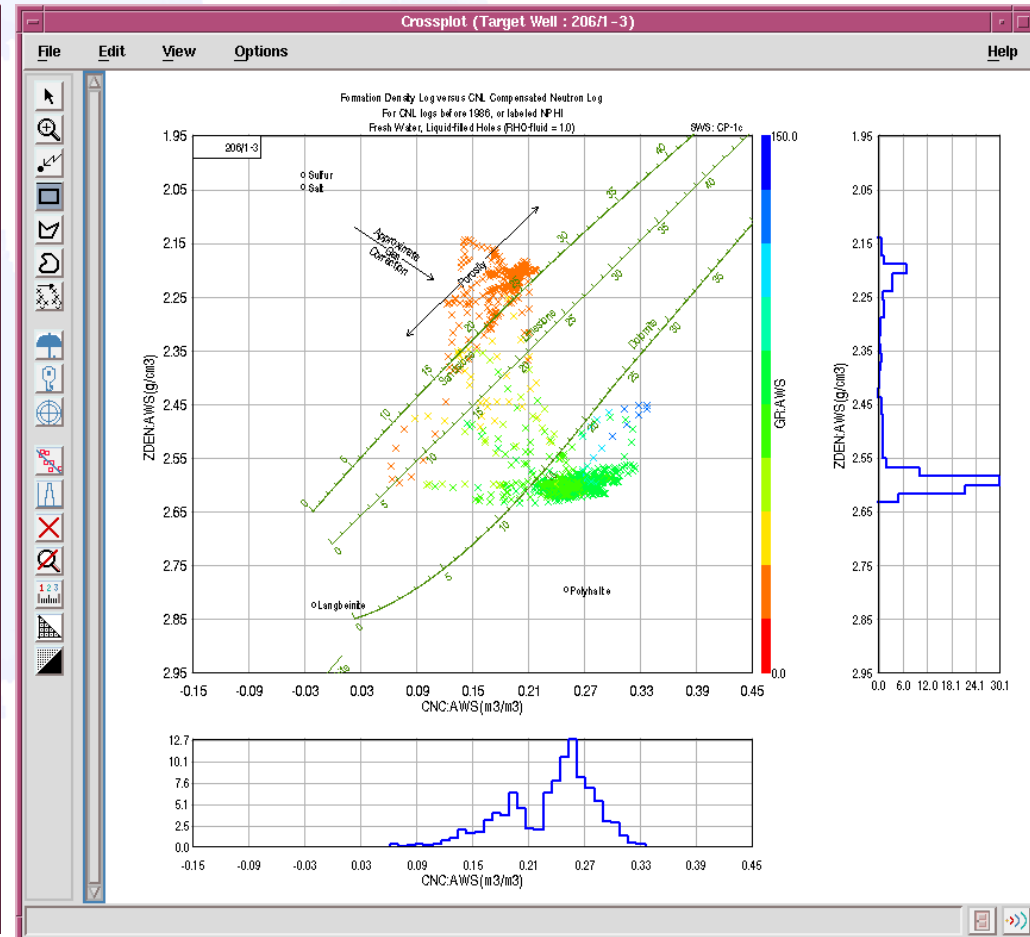
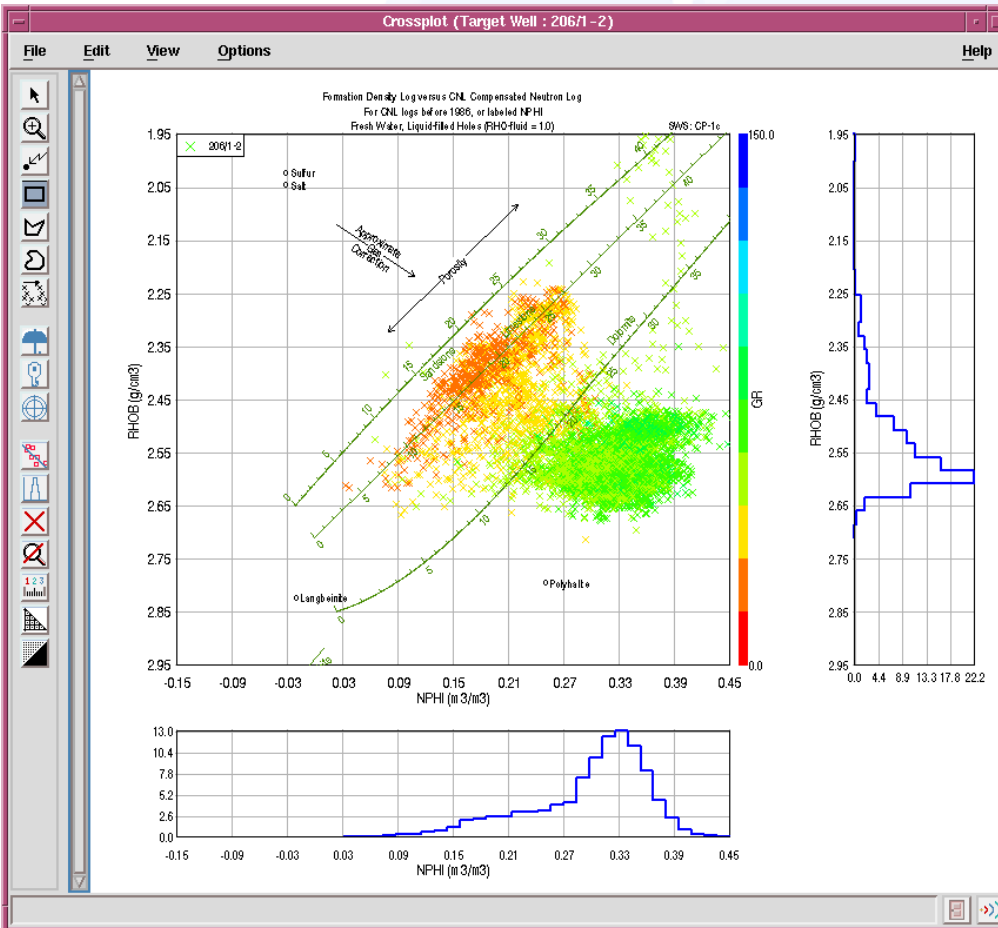
Porosity and Lithology Determination from Formation Density Log and CNL* Compensated Neutron Log

For CNL logs before 1966, or labeled NPHI

CP-1c



Xplot Density Neutron



POROSITY (Φ), defines the “storage” capacity of a reservoir.

The following logs are used to evaluate the porosity:

- DENSITY
- NEUTRON
- **SONIC**
- DIELECTRIC
- NUCLEAR MAGNETIC RESONANCE

Sonic Log

- The **sonic log** is a recording versus depth of the time required for a sound wave to traverse 1 ft of formation
- This time depends on:
 - Lithology
 - Porosity (which decreases the velocity of sound)
- Many acoustic energy arrivals are seen by the receivers of a digital sonic logging tool

Sonic Log

Sonic Log anomalies

- Non consolidated formations
- Cycle skipping
- Big holes

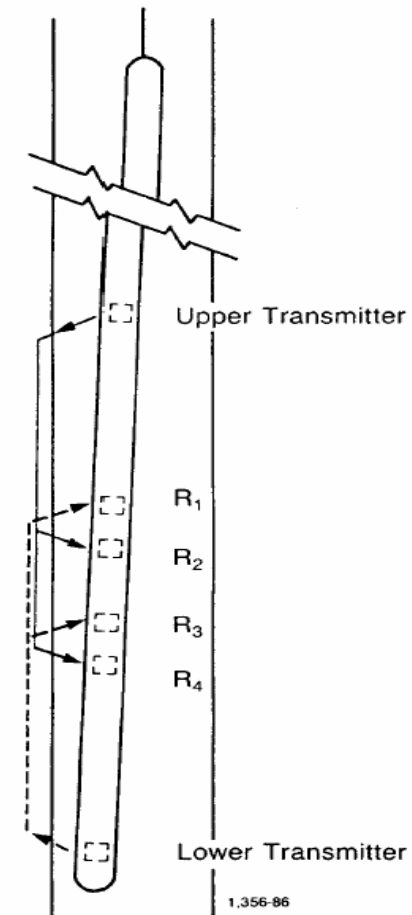
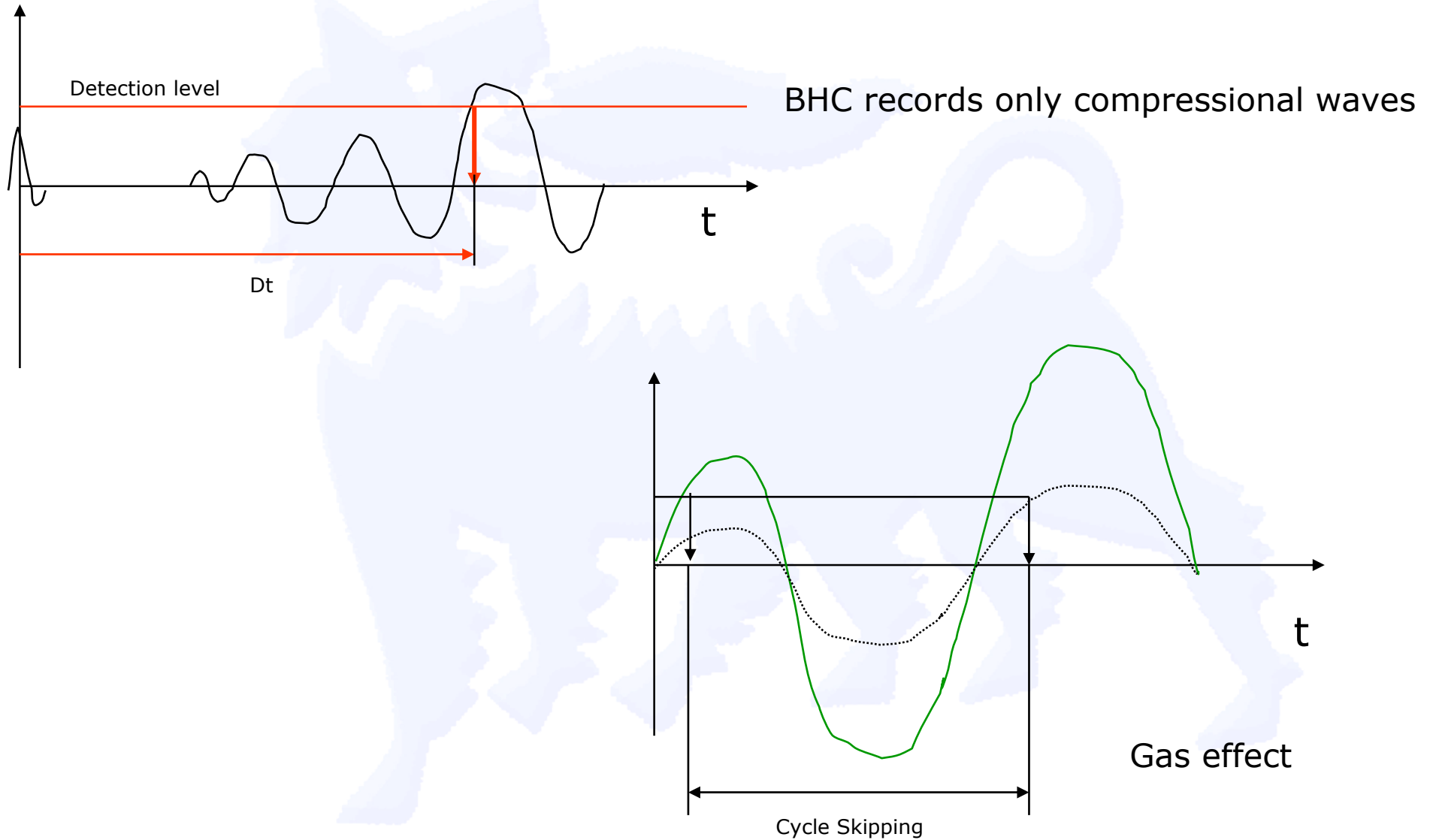
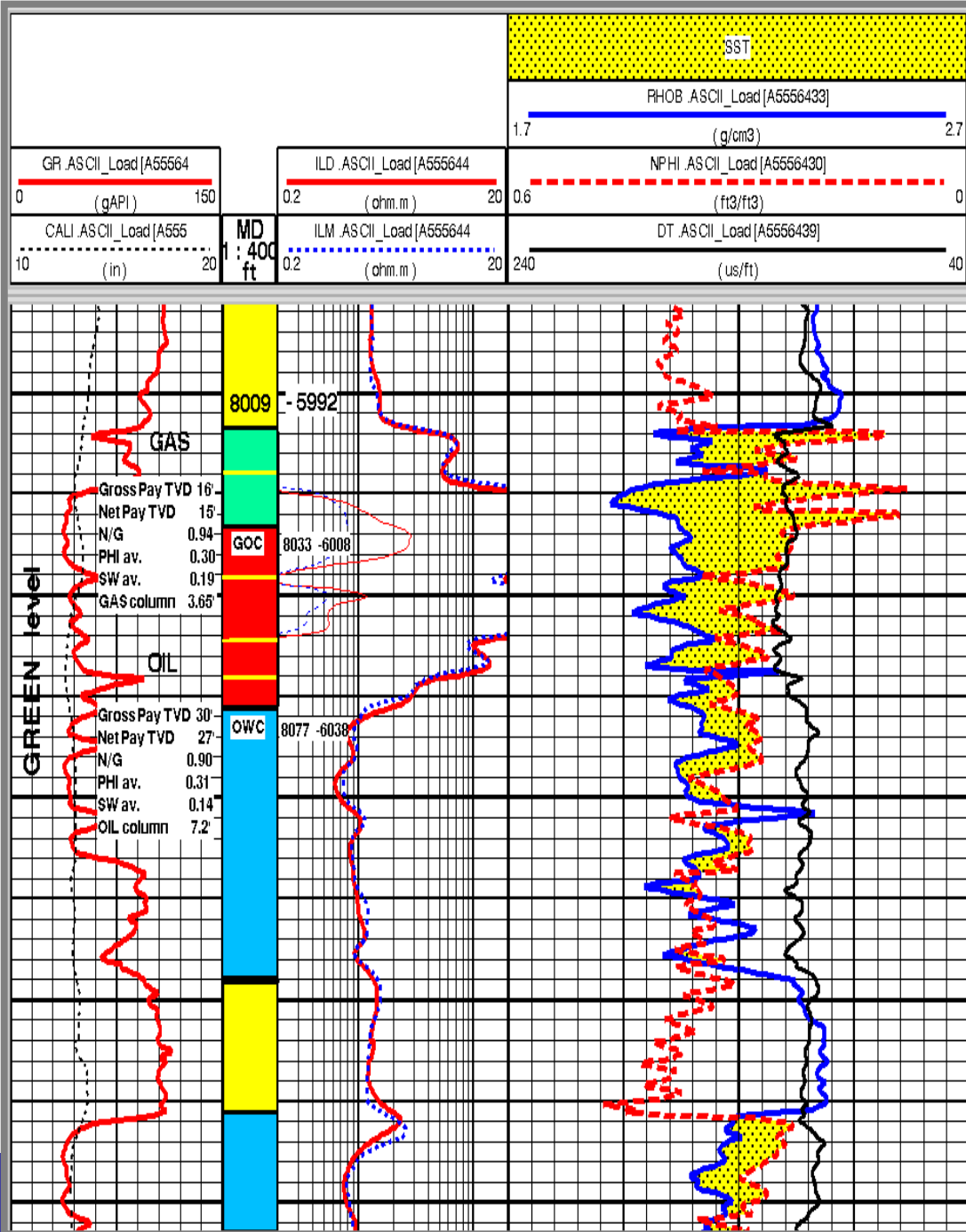


Figure C1: Schematic of BHC sonde, showing ray paths for the two transmitter-receiver sets. Averaging the two Δt measurements cancels errors from the sonde tilt and hole-size changes.

Sonic transit time detection

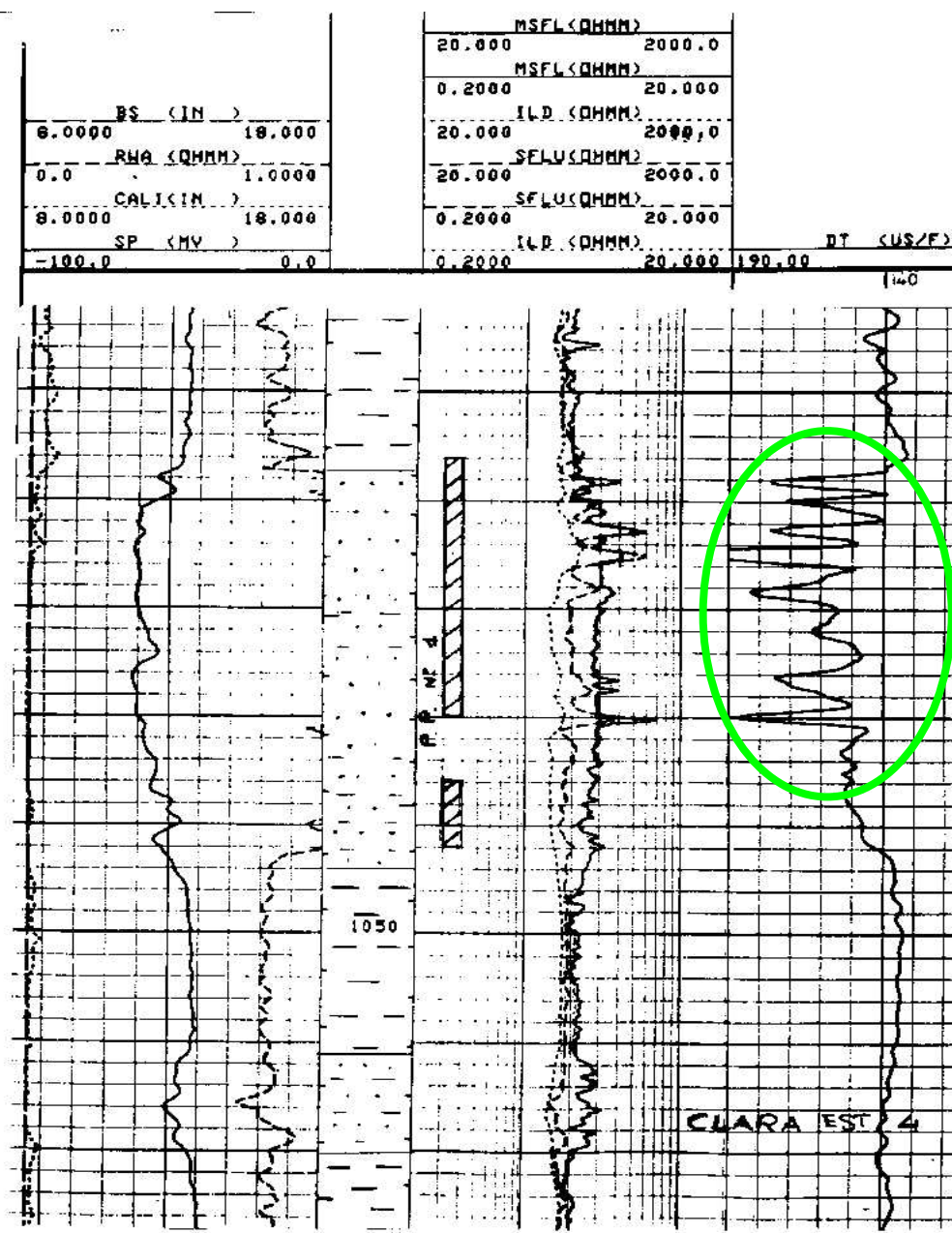




Sonic Log in clastic formations



Eni's Way



Sonic Log BHC

CYCLE SKIPPING
in gas bearing zone

Sonic Porosity Wyllie Time-Average Equation

$$t_{LOG} = \phi t_f + (1 - \phi) t_{ma}$$

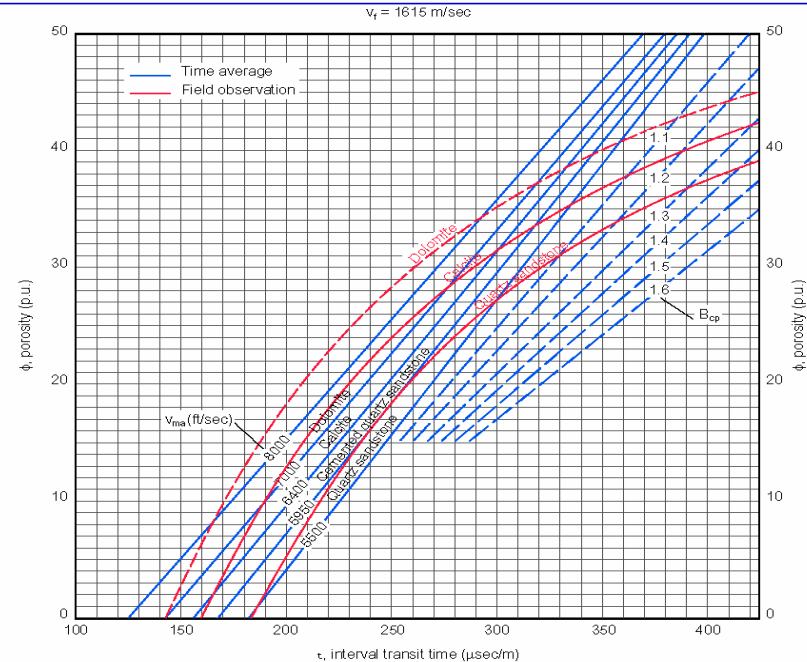
$$\text{or } \phi = \frac{t_{LOG} - t_{ma}}{t_f - t_{ma}}$$

Table 1

	v_{ma} (ft/sec)	Δt_{ma} (μs/ft)	Δt_{ma} (μs/ft) (commonly used)
Sandstones	18,000-19,500	55.5-51.0	55.5 or 51.0
Limestones	21,000-23,000	47.6-43.5	47.5
Dolomites	23,000	43.5	43.5
Anhydrite	20,000	50.0	50.0
Salt	15,000	66.7	67.0
Casing (Iron)	17,500	57.0	57.0

Porosity Evaluation from Sonic

$S_vf = 1615 \text{ m/s}$

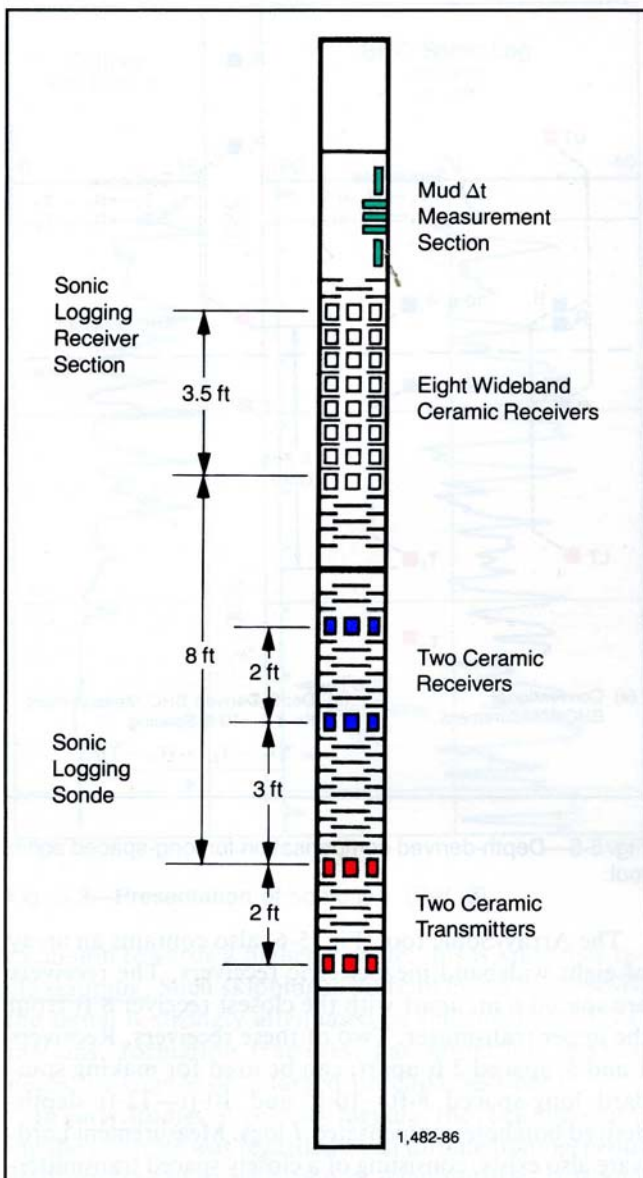


EXAMPLE: $t = 76 \mu\text{s/ft}$ (249 $\mu\text{s/m}$)
 $SV_{ma} = 19,500 \text{ ft/s}$ (5950 m/s) - Sandstone
 Thus, $\phi = 18\%$ (by either weighted average or empirical transform)

	SV_{ma} (ft/s)	t_{ma} (μs/ft)	SV_{ma} (m/s)	t_{ma} (μs/m)
Sandstones	18,000 - 19,500	55.5 - 51.3	5486 - 5944	182 - 168
Limestones	21,000 - 23,000	47.6 - 43.5	6400 - 7010	156 - 143
Dolomites	23,000	43.5	7010	143

Por-3m

Figure C6

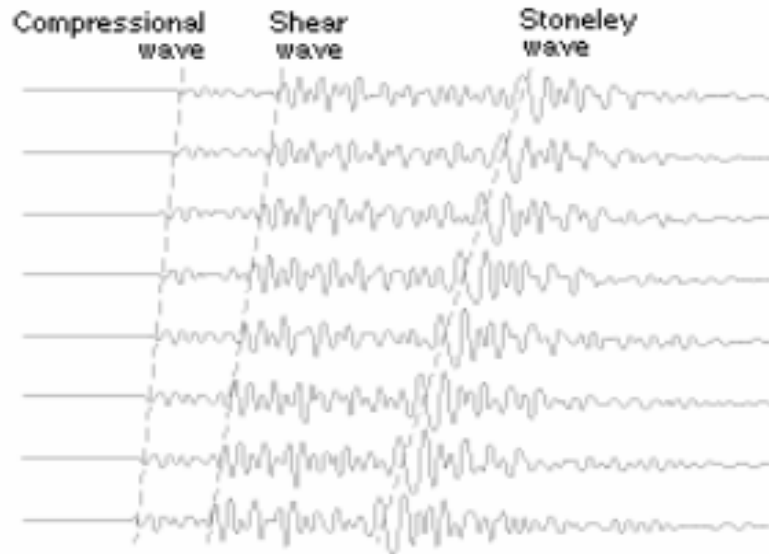
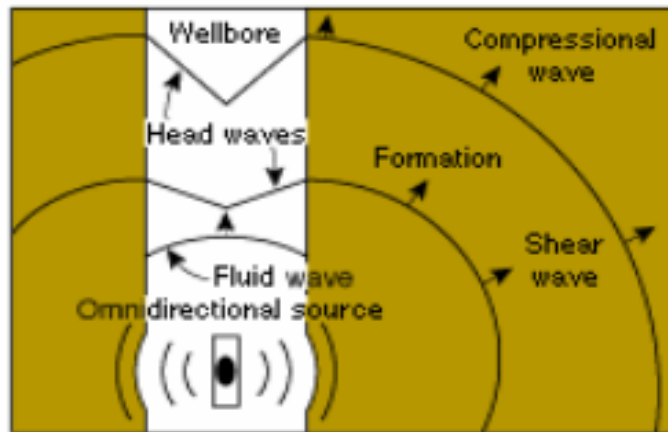


Sonic Logs: Digital Tools

Array Sonic

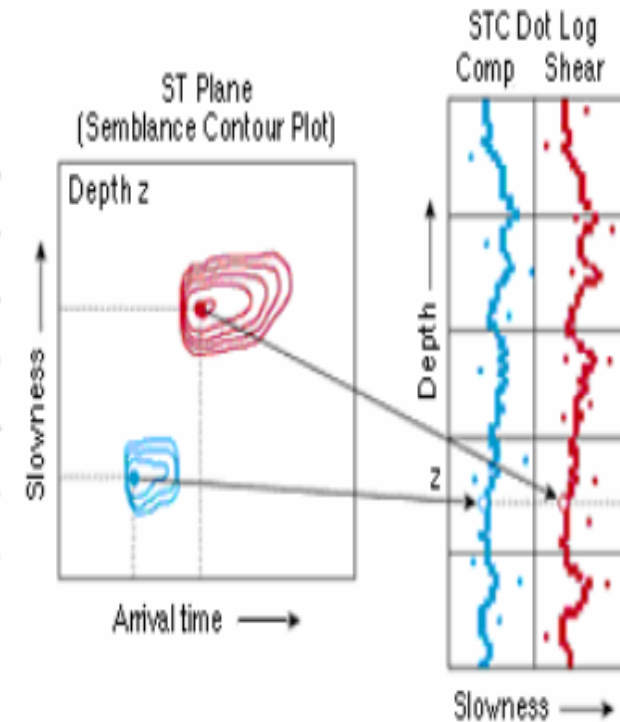
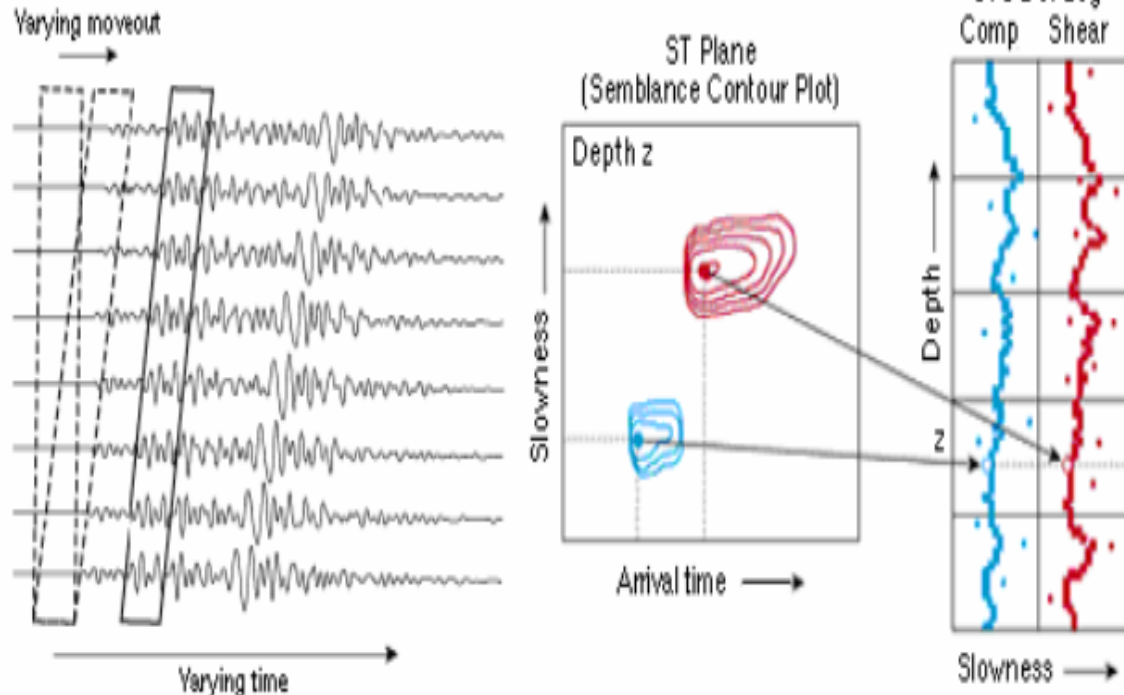
- 2 transmitters 2ft spaced and 2 Receiver 3 and 5 ft from the uppermost transmitter.
- A string of 8 receivers spaced 3,5 ft and 8 ft from the uppermost transmitter.
- The complete vaweform is analyzed

SONIC LOG: digital tools



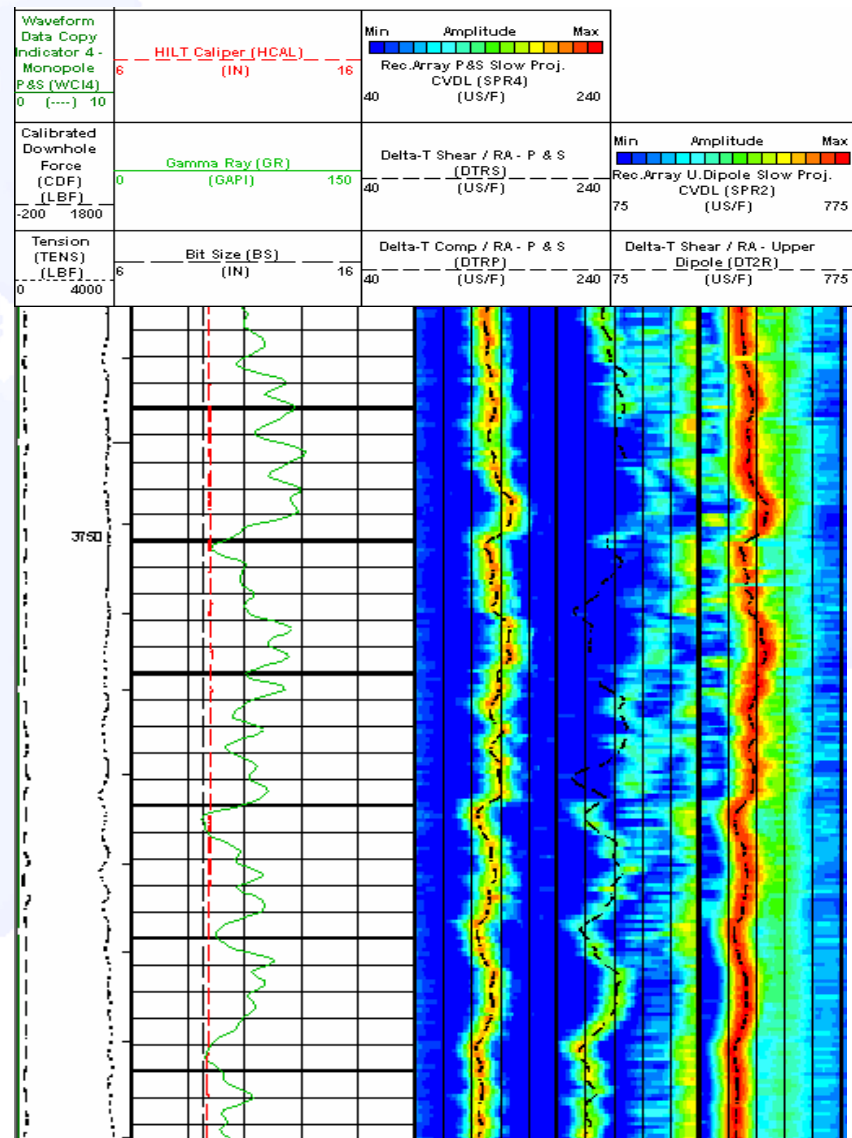
- First arrival compressional wave
- Shear wave
- Stoneley wave

Wave Form Analysis – STC Slowness-Time Coherence Technique



- The complete waveform is analysed and by an algorithm of coherence a DT is computed for the different waves.
- Using coherence maps the DT compressional, shear and Stoneley are defined
- This process is applied to every set of waveform and a sonic log is generated.

EXAMPLE OF DIGITAL LOG



POROSITY (Φ), defines the “storage” capacity of a reservoir.

The following logs are used to evaluate the porosity:

- DENSITY
- NEUTRON
- SONIC
- DIELECTRIC
- **NUCLEAR MAGNETIC RESONANCE**

Nuclear Magnetic Resonance

Basics of NMR measurements

Nuclear Magnetic Resonance refers to the response of nuclei to a magnetic field.

Many nuclei have a magnetic moment and they behave like spinning bar magnets.

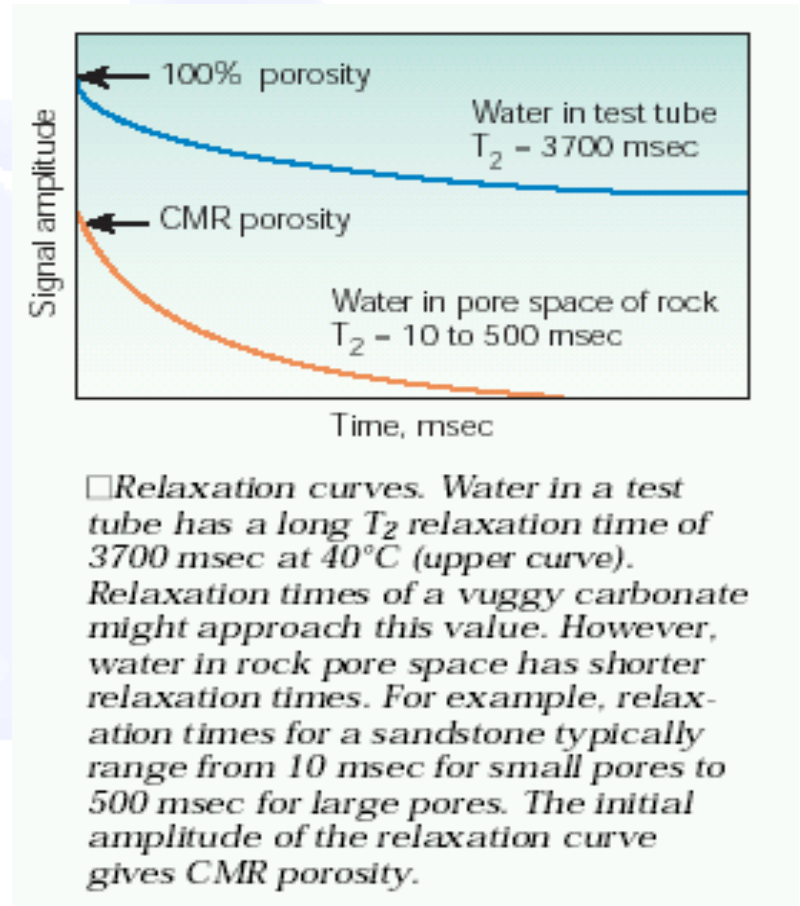
These spinning magnetic nuclei can interact with externally applied magnetic fields, producing measurable signals.

Among many other elements distributed in the subsurface formations, hydrogen has a relatively large magnetic moment and hydrogen is abundant in both water and hydrocarbons.

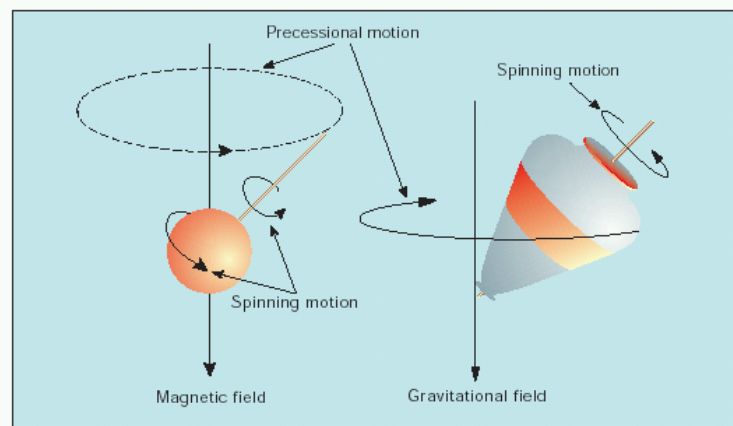
By tuning NMR logging tools to the magnetic resonant frequency of hydrogen, the signal is maximized and can be measured.

The quantities measured are signal amplitude and decay.

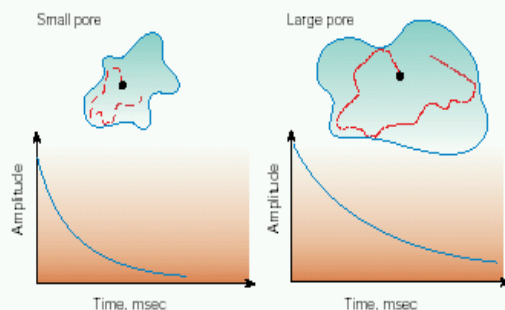
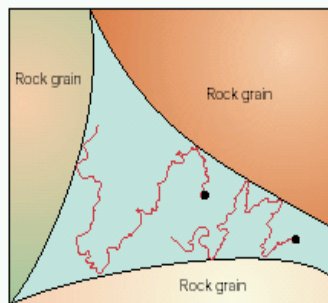
NMR signal amplitude is proportional to the number of hydrogen nuclei present and is calibrated to give porosity, free from radioactive sources and free lithology effects.



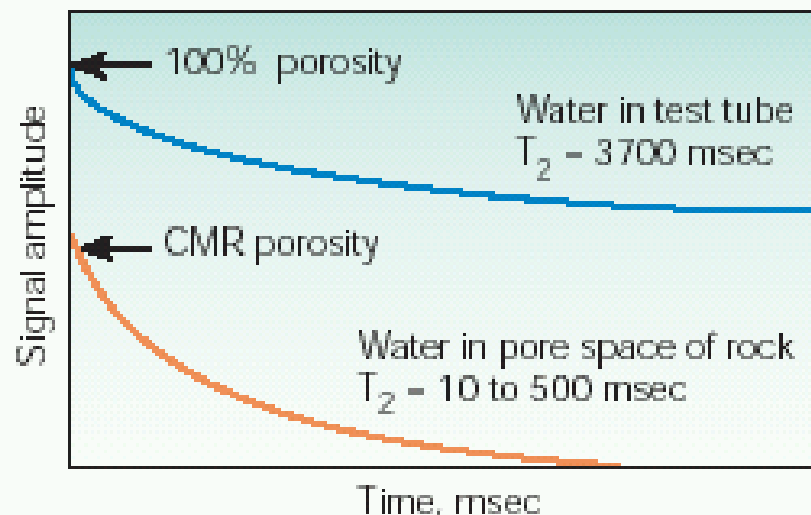
Nuclear Magnetic Resonance



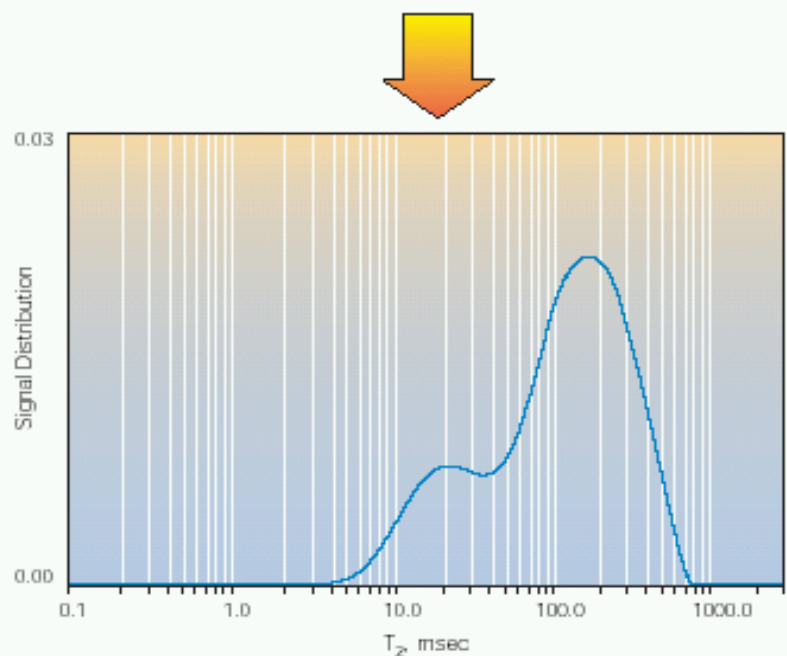
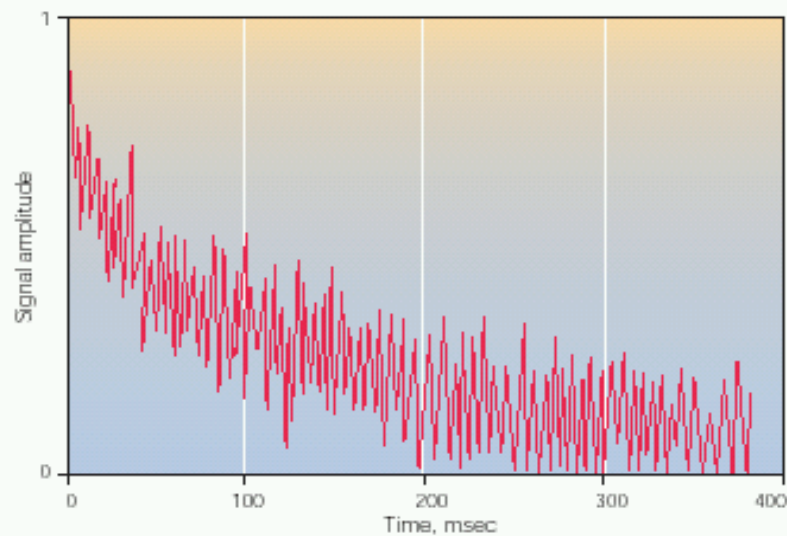
□ **Precessing protons.** Hydrogen nuclei—protons—behave like spinning bar magnets. Once disturbed from equilibrium, they precess about the static magnetic field (left) in the same way that a child's spinning top precesses in the Earth's gravitational field (right).



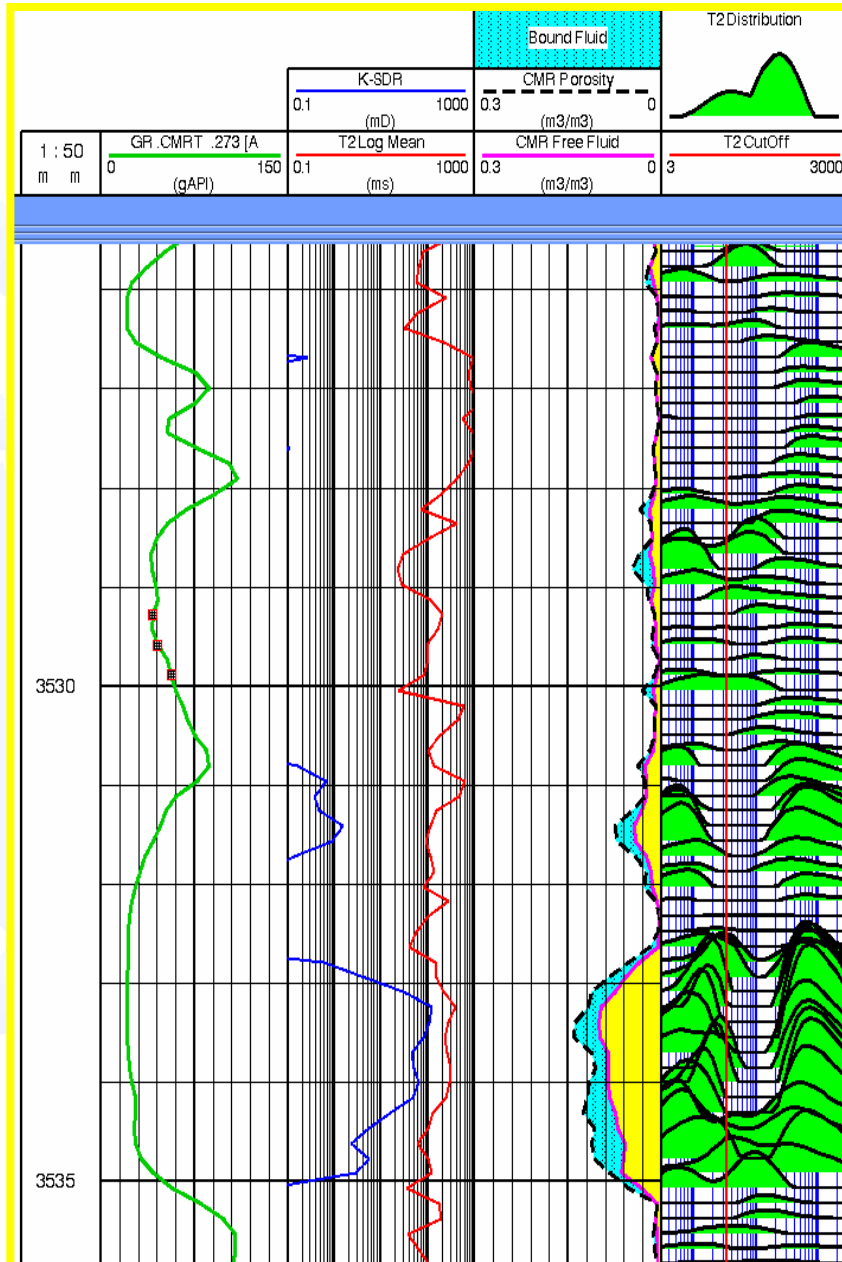
□ **Grain surface relaxation.** Precessing protons move about pore space colliding with other protons and with grain surfaces (left). Every time a proton collides with a grain surface there is a possibility of a relaxation interaction occurring. Grain surface relaxation is the most important process affecting T_1 and T_2 relaxation times. Experimenters have shown that when the probability of colliding with a grain surface is high—small pores (center)—relaxation is rapid and when the probability of colliding with a grain surface is low—large pores (right)—relaxation is slower.



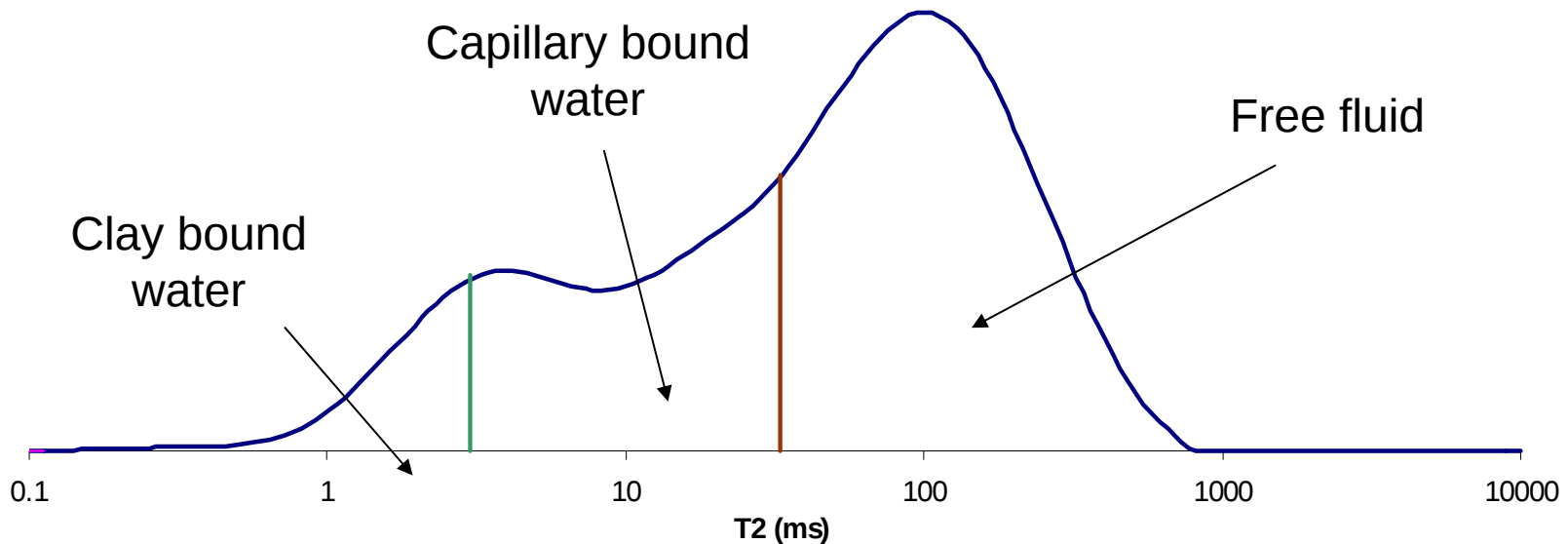
□ **Relaxation curves.** Water in a test tube has a long T_2 relaxation time of 3700 msec at 40°C (upper curve). Relaxation times of a vuggy carbonate might approach this value. However, water in rock pore space has shorter relaxation times. For example, relaxation times for a sandstone typically range from 10 msec for small pores to 500 msec for large pores. The initial amplitude of the relaxation curve gives CMR porosity.



Signal amplitude processed to give T_2 distribution. The CMR tool measures decaying NMR signal amplitude (top), which is the sum of all the decaying T_2 signals generated by hydrogen protons in the measurement volume. Separating out ranges of T_2 values by a mathematical inversion process produces the T_2 distribution (bottom). The curve represents the distribution of pore sizes, and the area under the curve is CMR porosity. Interpretation of pore size distribution and logarithmic mean T_2 are used to calculate such parameters as permeability and free-fluid porosity.



T_2 distribution curve



In a water saturated rock, the relaxation time, T_2 , is related to the pore size: the smaller the pore, the faster the relaxation.

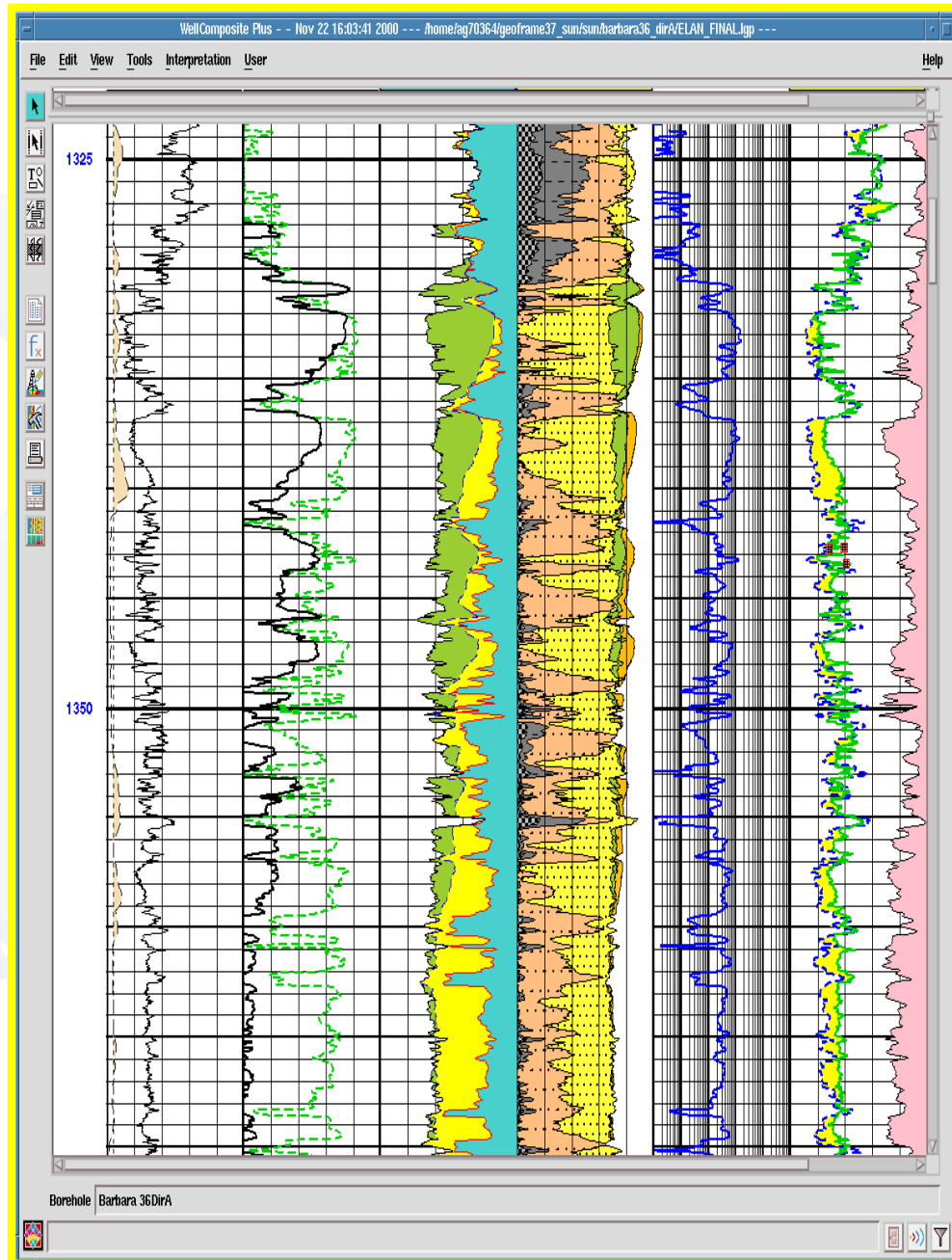
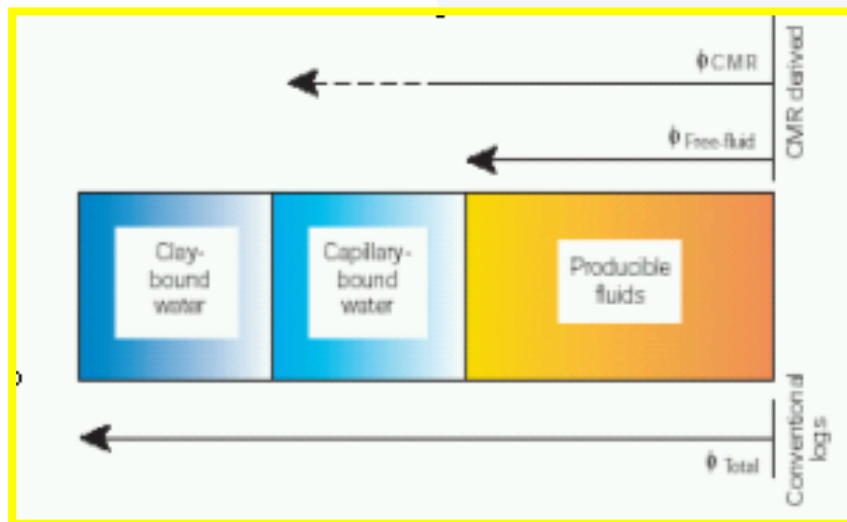
On the basis of T_2 , the porosity can be divided into

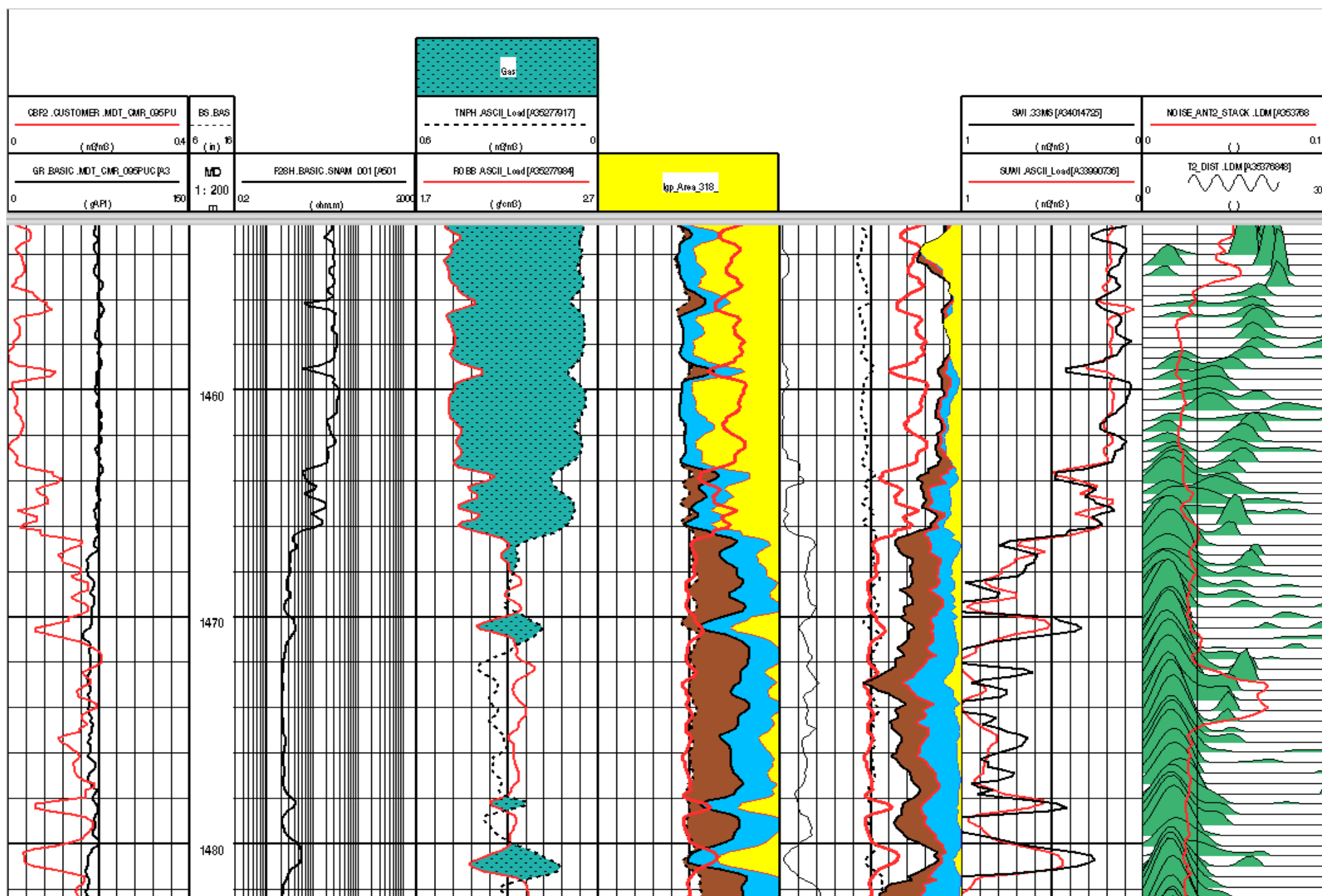
- Clay-bound water ($T_2 < 3$ ms)
- Capillary bound water ($3 \text{ ms} < T_2 < T_2 \text{ cut-off}$)
- Free fluid ($T_2 > T_2 \text{ cut-off}$)

Nuclear Magnetic Resonance

NMR log can define:

- Effective Porosity;
- Permeability;
- Irreducible Water Saturation;
- Movable Fluid Saturation;



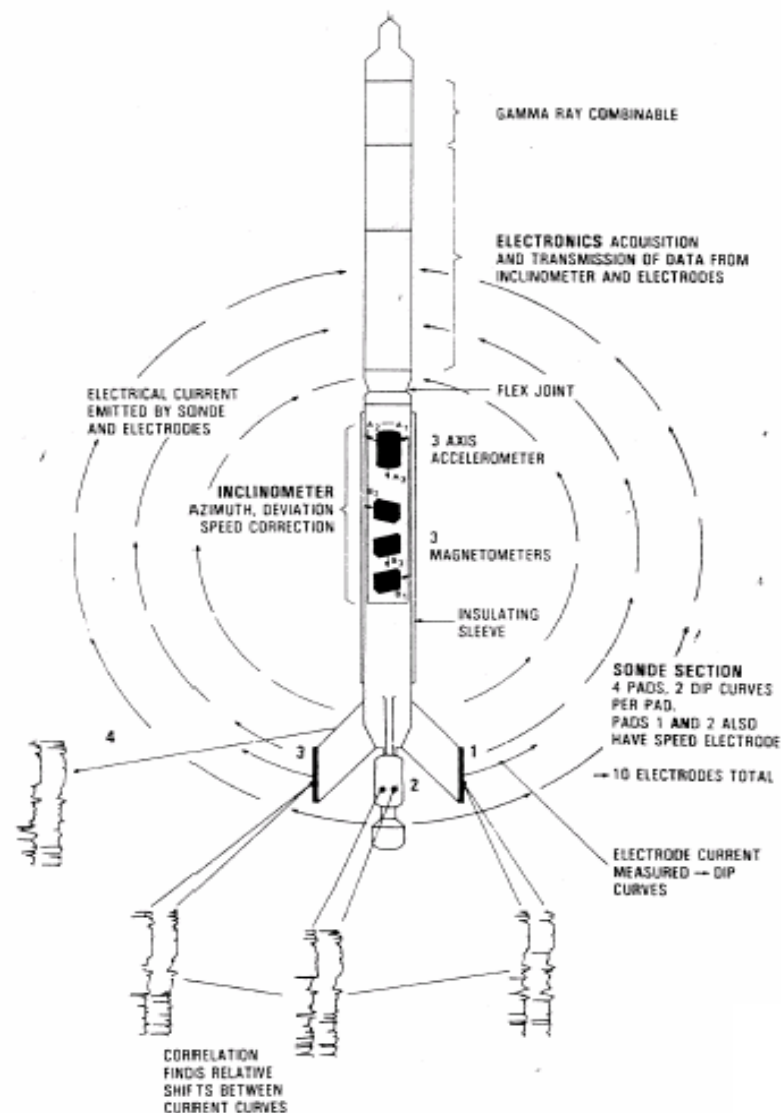
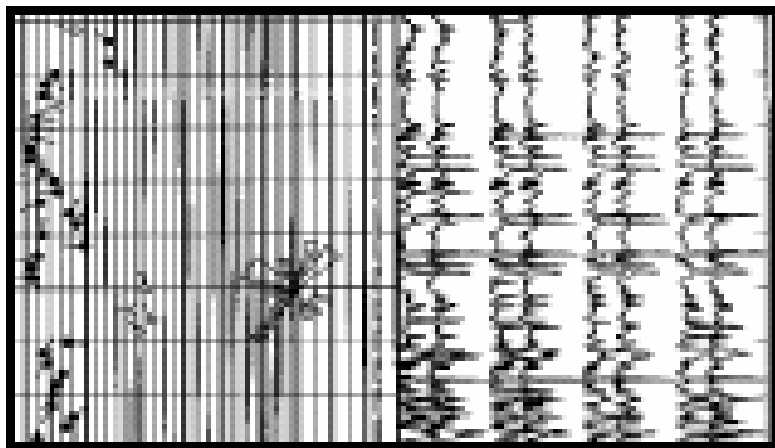


To derive TEXTURE and **STRUCTURAL** setting:

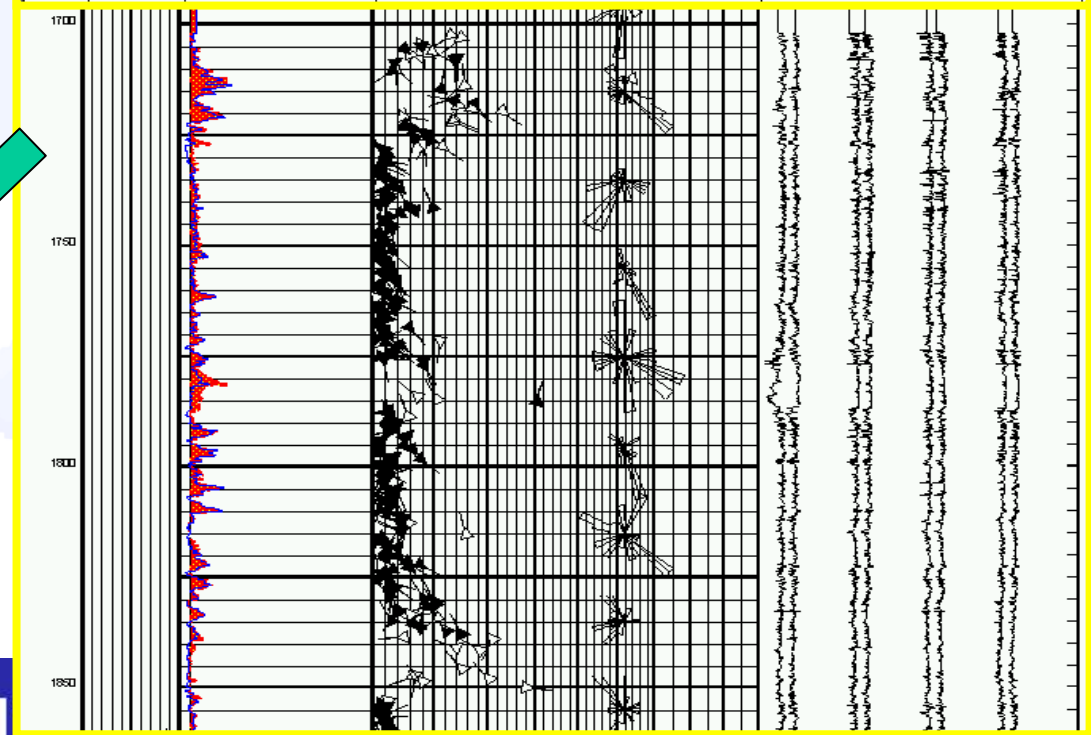
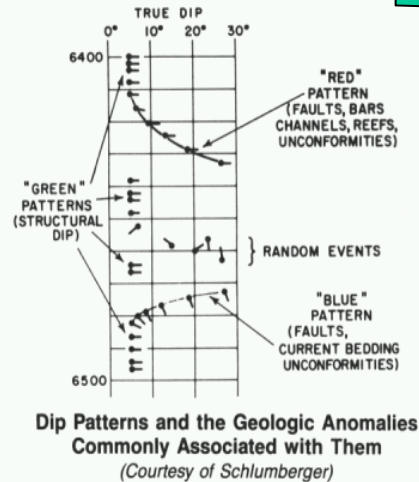
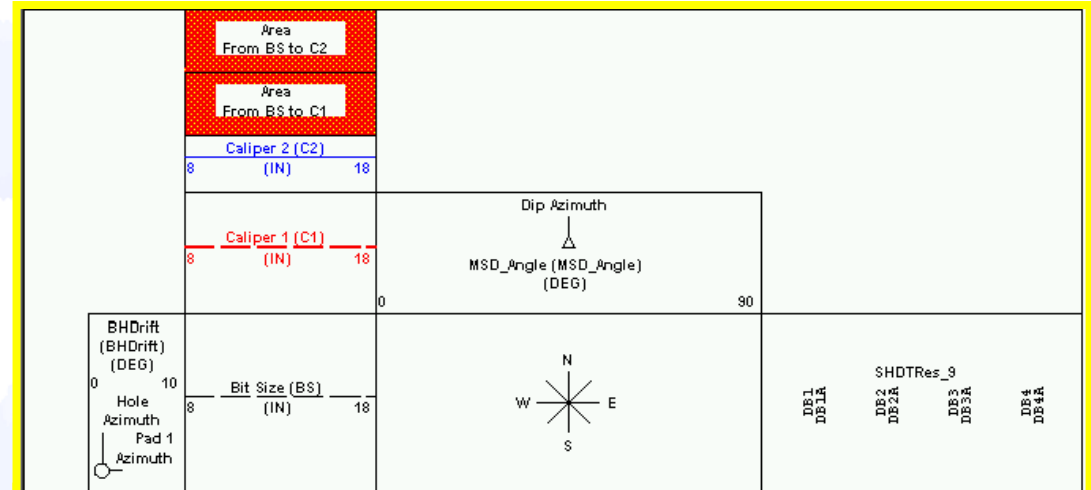
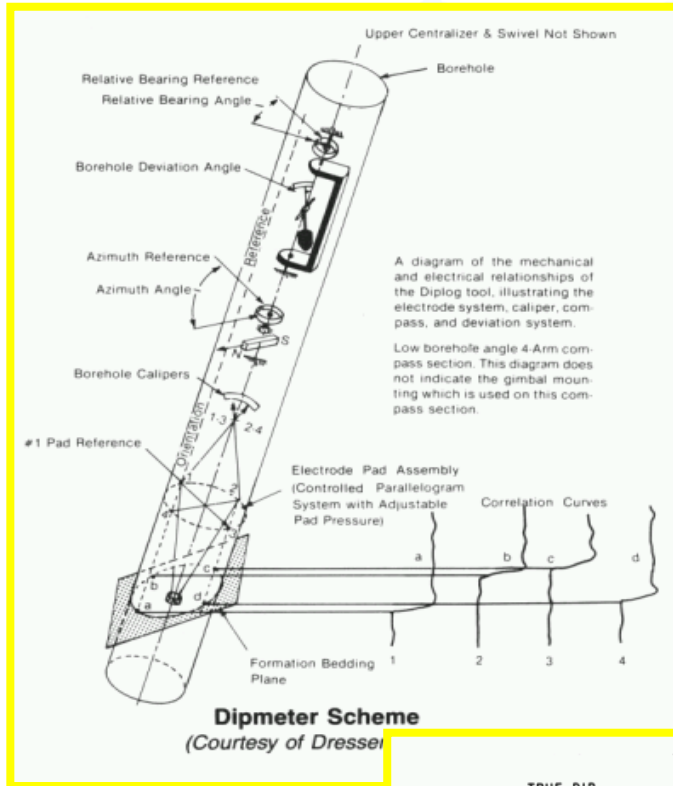
- **IMAGE LOGS, Dipmeter, Sonic**
- **IMAGE LOGS, Dipmeter**

Stratigraphic High Resolution Dipmeter Tool (SHDT)

- 4 arm sonde design
- 2 dip buttons per pad
- 3 axis accelerometer and 3 magnetometer inclinometry cartridge

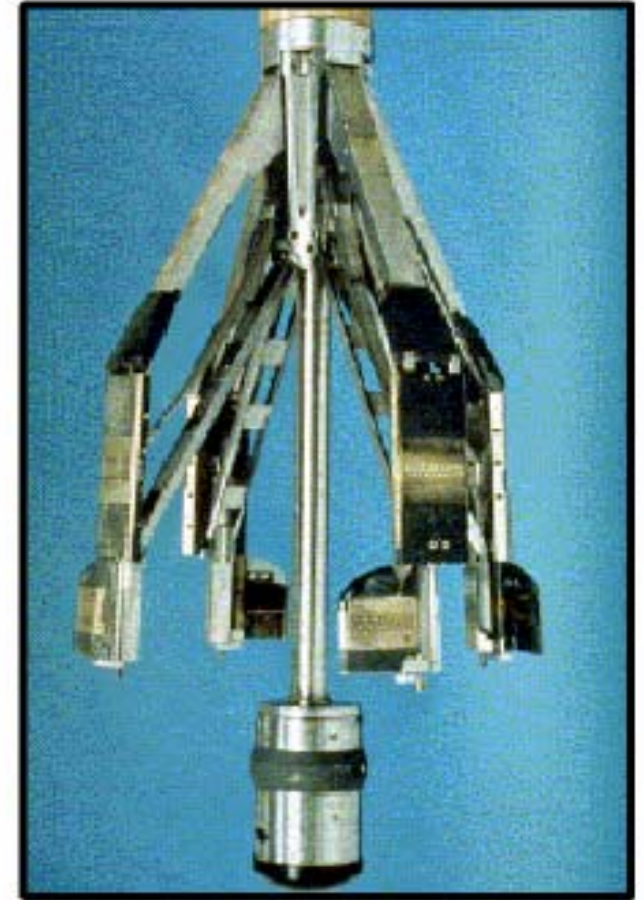


Well Logs: structural analysis

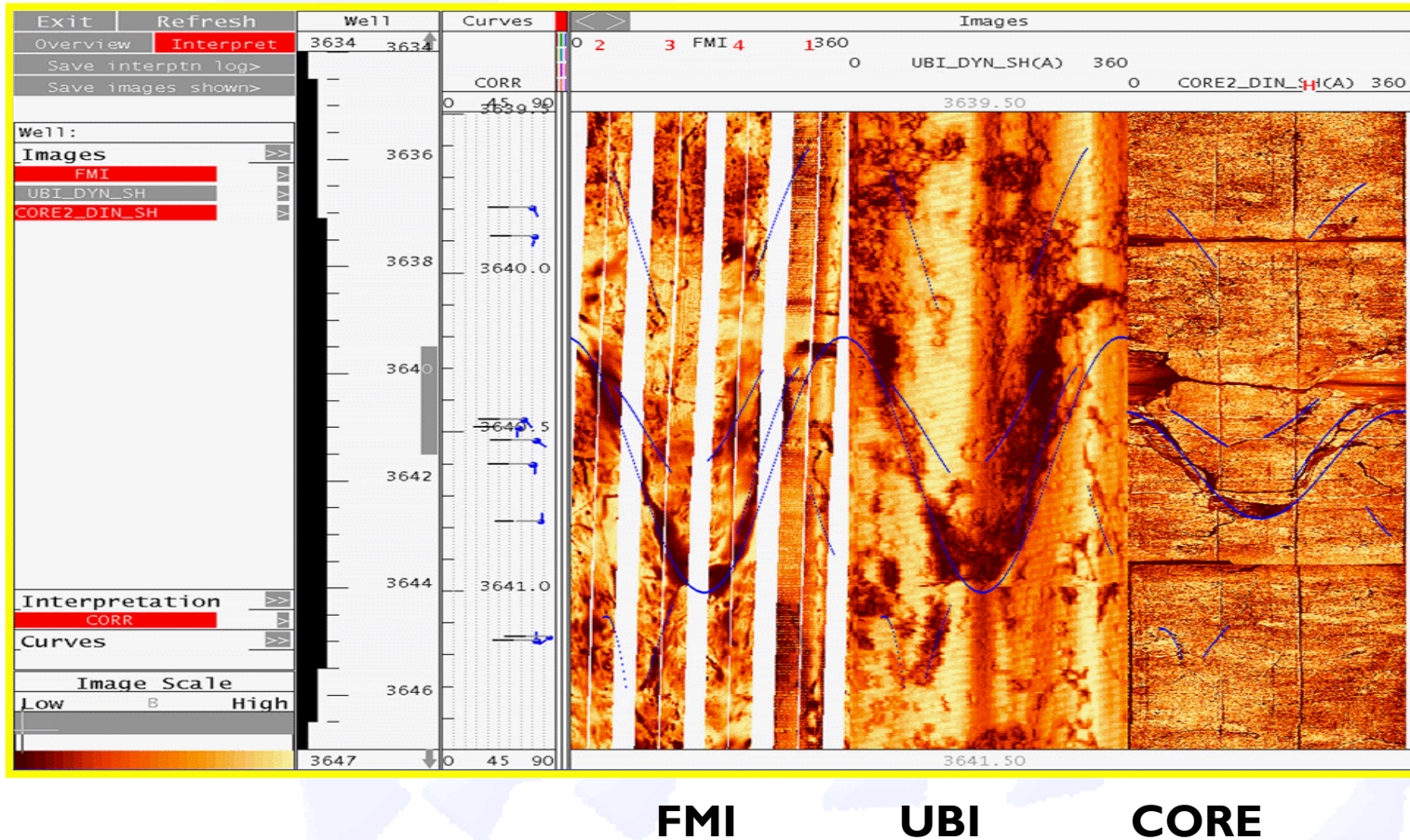


FMS Specifications

- Length 31 ft [9.45 m]
- Weight 537 lb [243 kg]
- Tool diameter 5.0 in. [127 mm]
- Minimum hole size FMSC 6.25 in. (160 mm)
FMSB 4.5 in (114 mm)
- Maximum opening diameter FMSC 21 in. (533 mm)
FMSB 15 in (381 mm)
- Pressure rating 20,000 psi [1400 bars]
- Temperature rating 350°F [175°C]
- Logging speed
 - Dip and Images 1600 ft/hr [500 m/hr]
 - Dip only 3200 ft/hr [1000 m/
- Tool Resolution 0.2-0.3 in
- Sampling rate 0.1 in (2.5 mm)
- Coverage FMSC 40% in 8 in borehole
FMSB 40% in 6 in borehole



Well Logs: Geological Applications



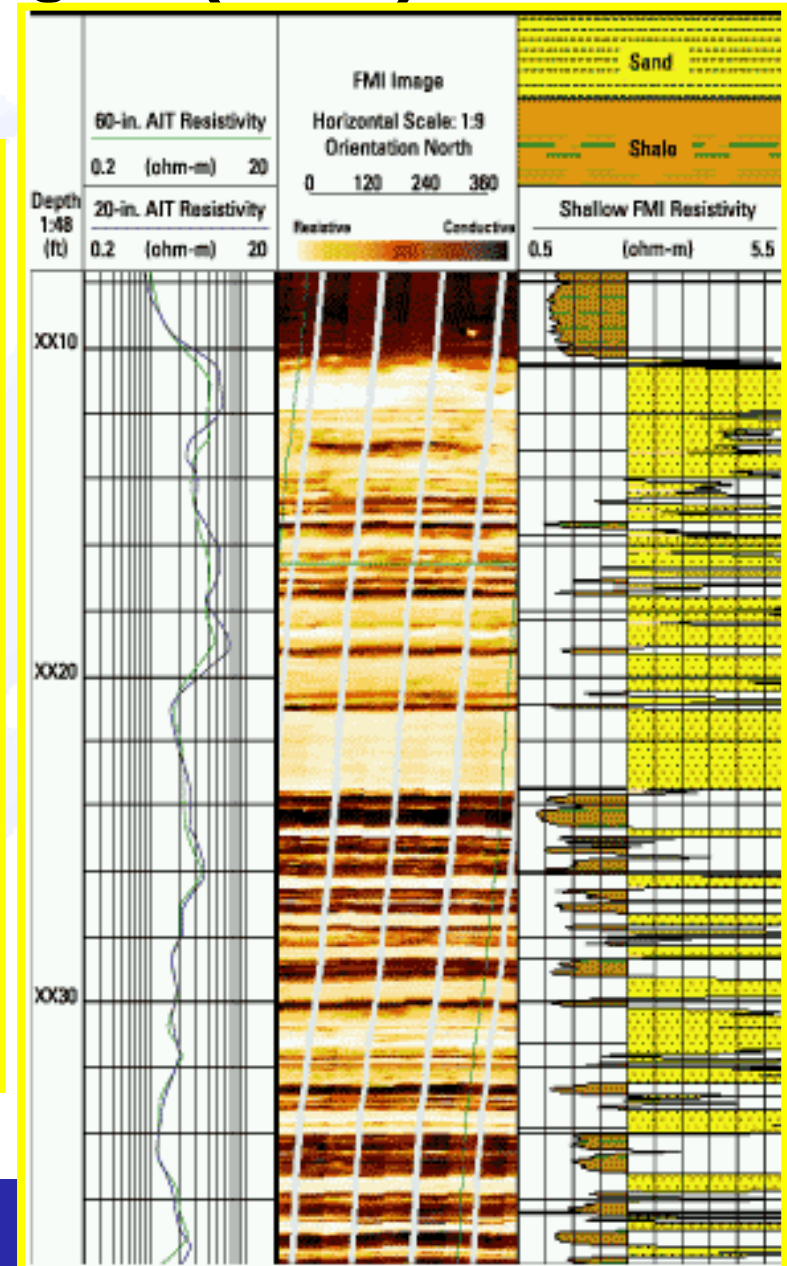
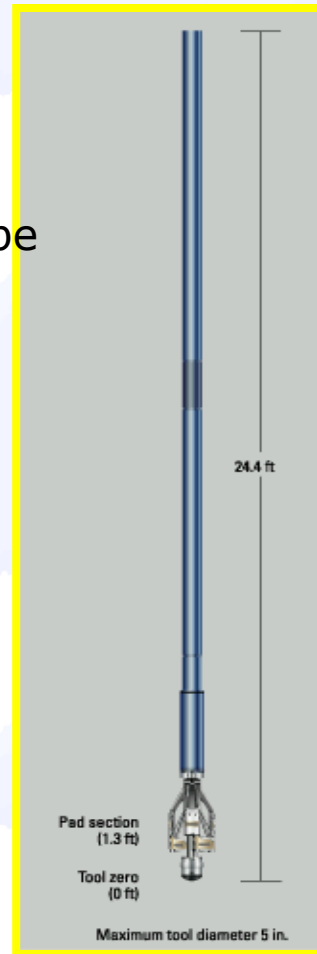
Imaging Logs (oriented electrical a/o acoustic images) can be used in: petrophysics, structural analysis, geomechanics, sedimentology.

Formation Micro Imager (FMI)

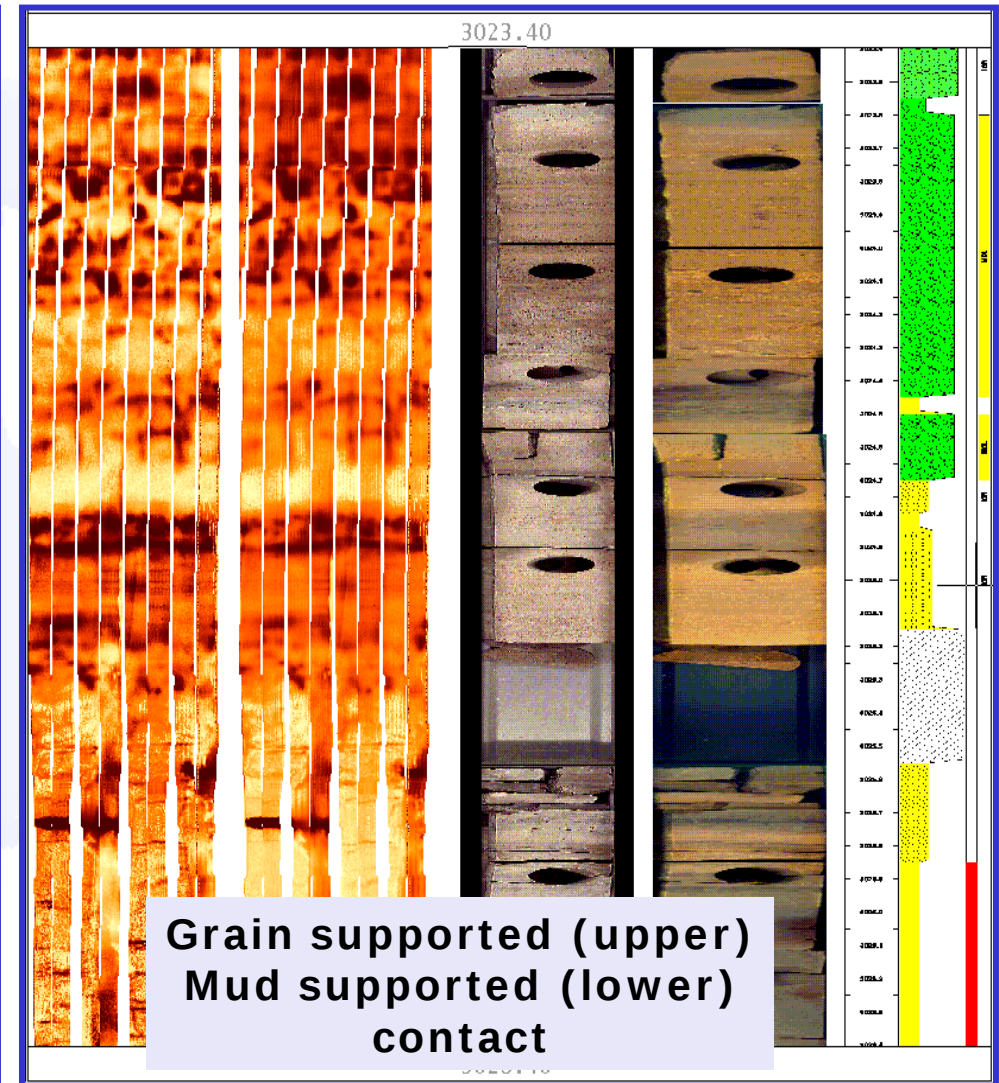
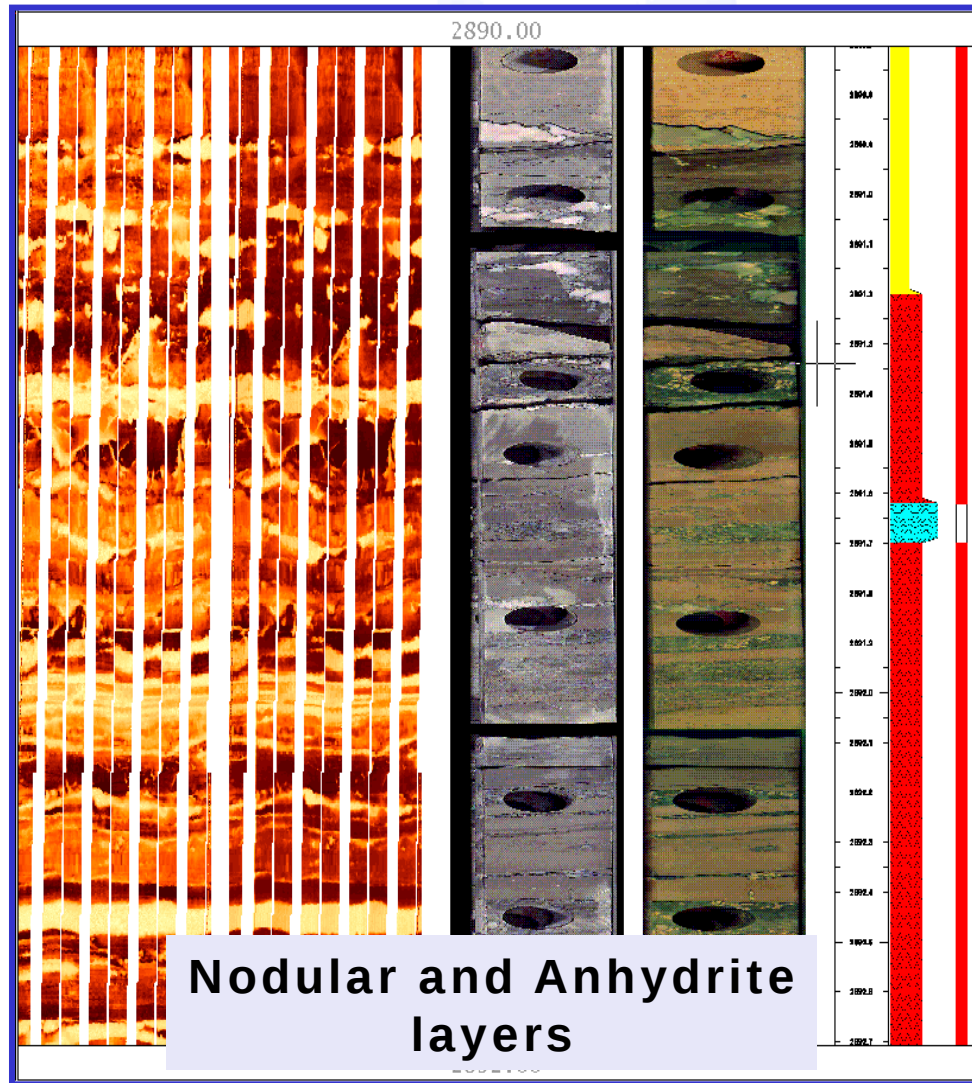
This tool produces oriented “electrical” imaging of the borehole wall, with very high vertical resolution (0,2 inch) only in conductive mud (WBM).

Using this tool the following studies can be performed:

- structural;
- textural;
- sedimentological;
- net pay evaluation in thin layer reservoirs;
- fracture analyses;
- stress in situ.

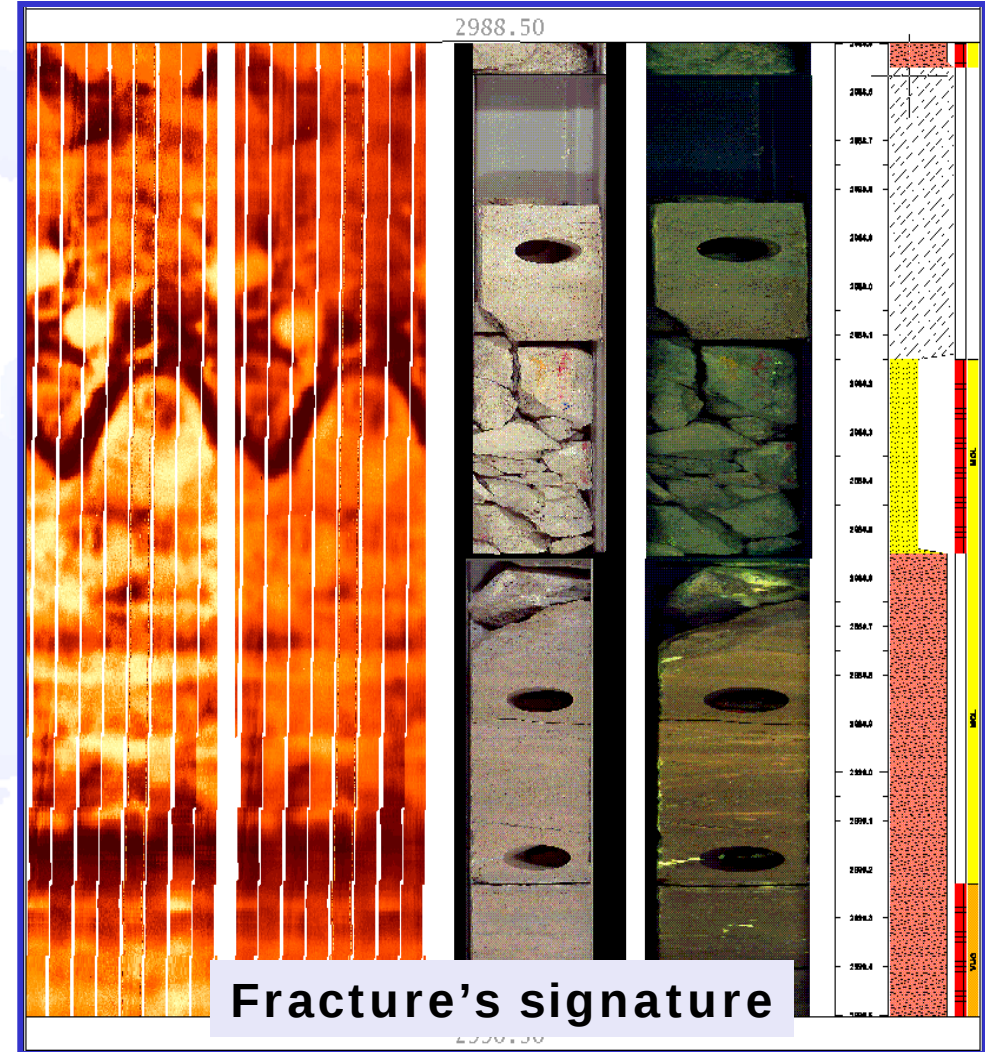
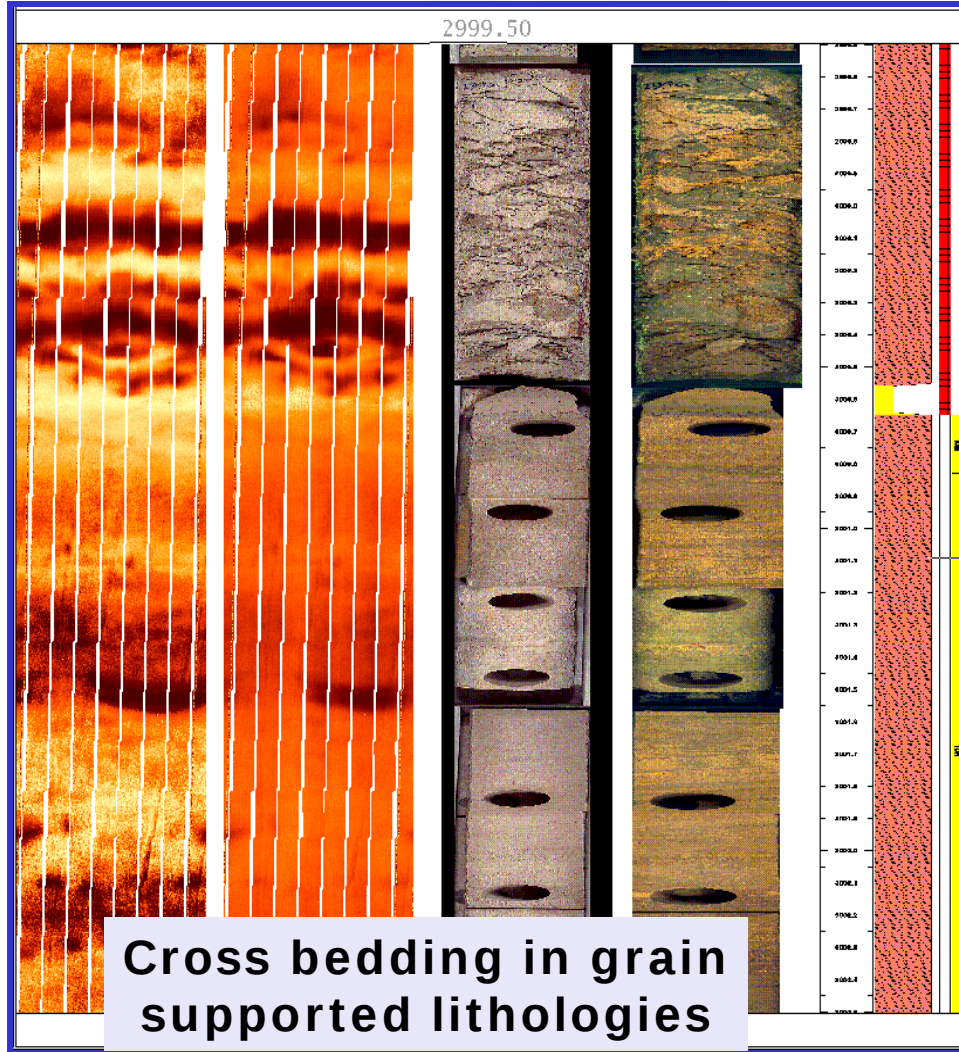


FMI Borehole Images



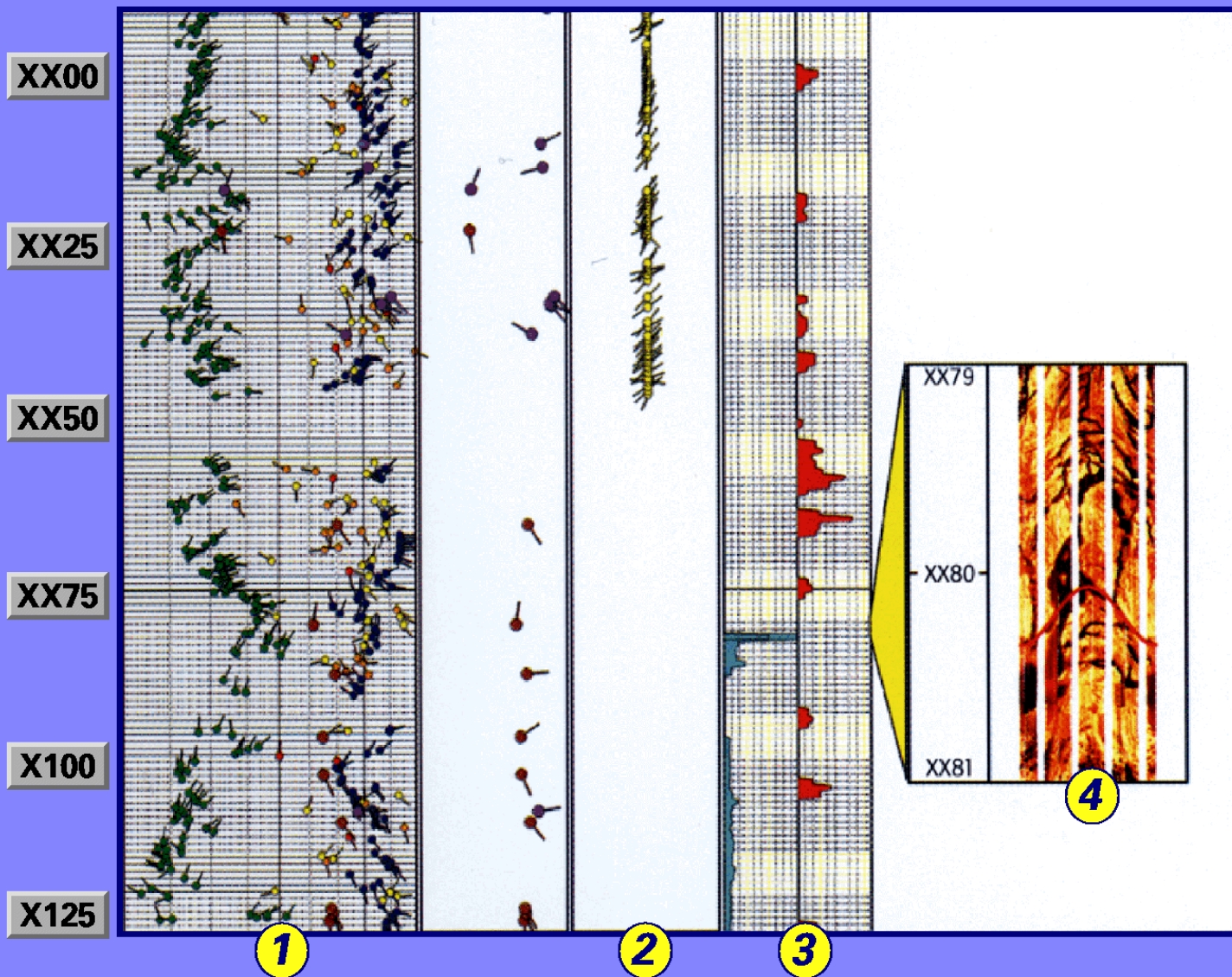
Textural information from FMI vs sedimentological data from cores

FMI Borehole Images



Textural information from FMI vs sedimentological data from cores

Well Logs: geological applications



INTEGRATION BETWEEN

1

**STRUCTURAL
COMPUTATION**

2

**BREAK OUT/
FAULT DETECTION**

3

**MUD LOSSES/
GAS PRESENCE**

4

FMI IMAGES

Use of imaging logs for detailed fracture network characterization in carbonates

Ultrasonic Borehole Imager (UBI)

This tool gives us “acoustics” oriented images of the borehole wall.

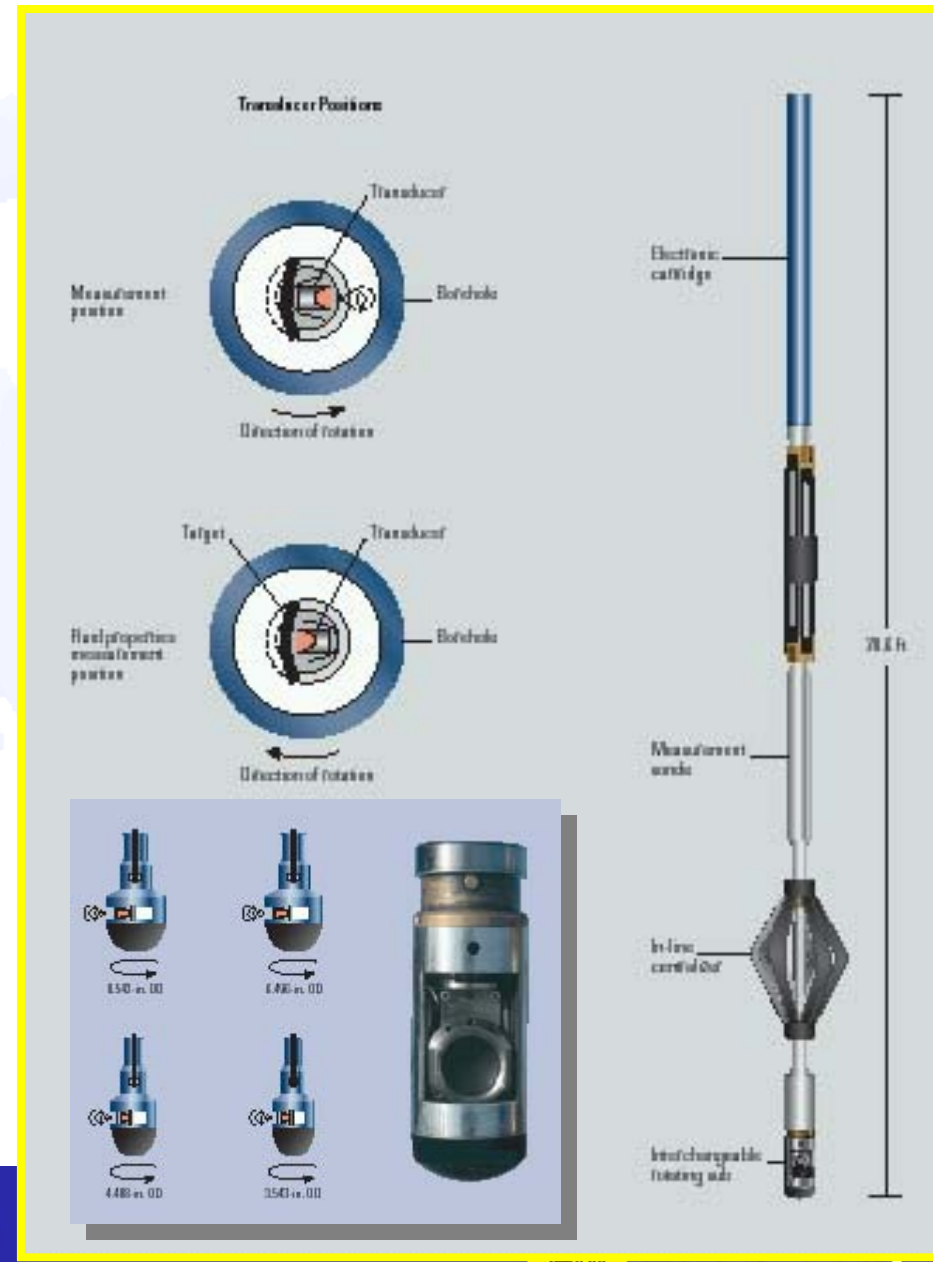
These images can be derived from the transit time of the high frequency acoustic wave, or from the attenuation of the signal which is function of the acoustic impedance of the rock.

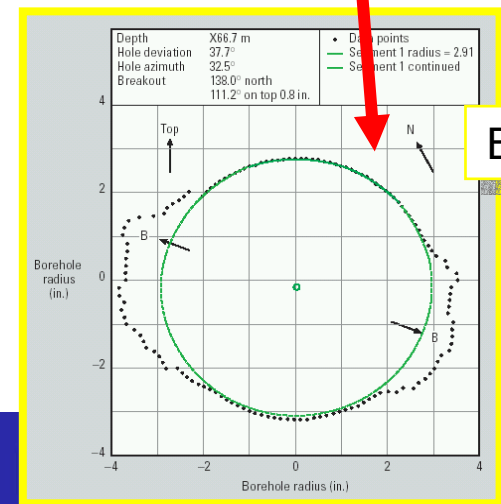
Informations about the borehole shape are derived from the transit time.

Information about the rock type are derived from the attenuation.

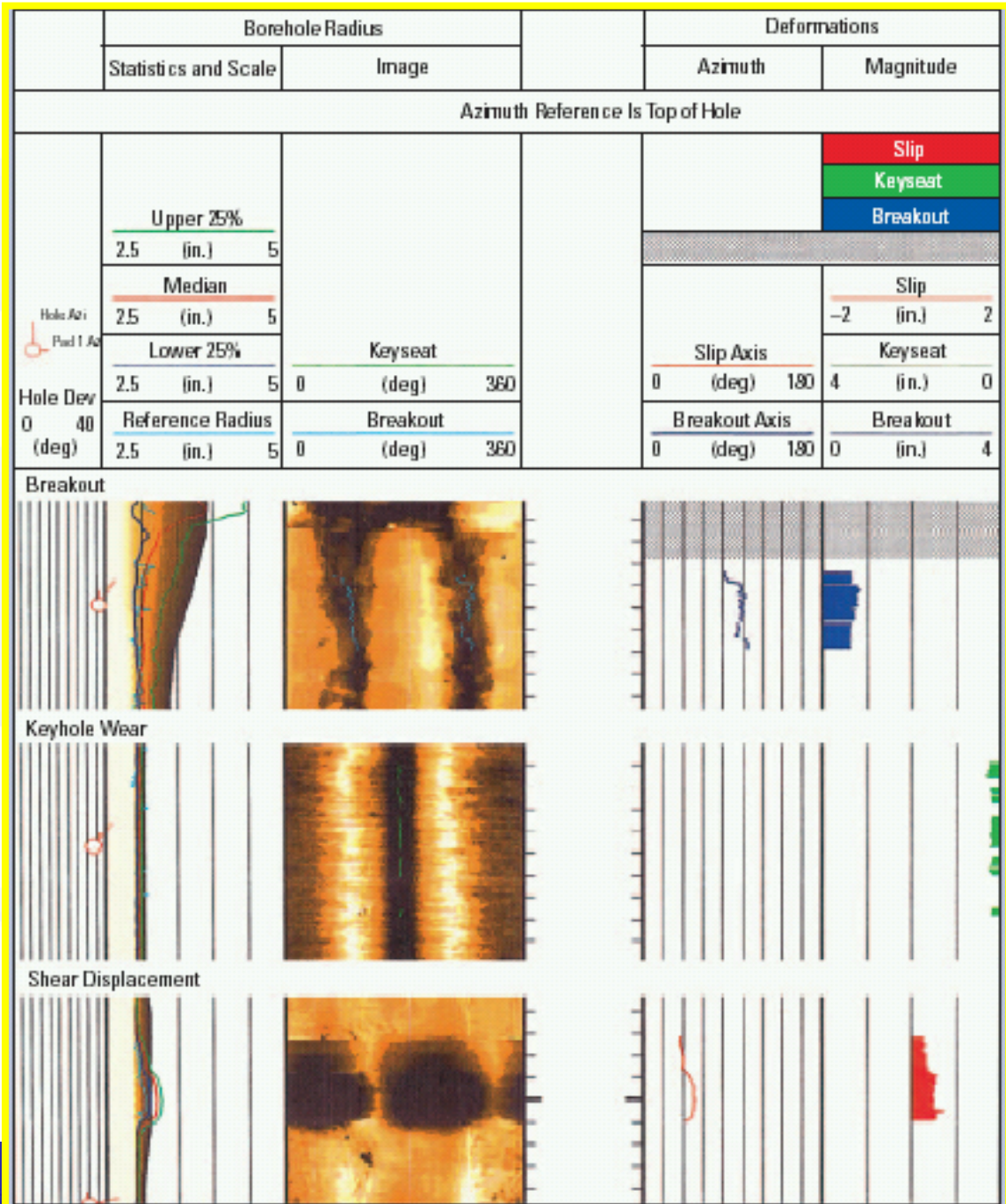
The main applications are:

- structural evaluation (faults and beds setting);
- fracture identification and characterization;
- borehole shape analysis to evaluate stability, stress in situ, cement volume.

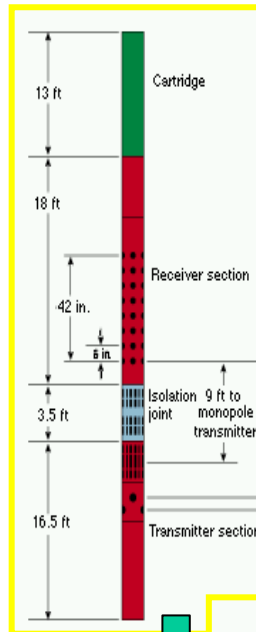




Break Out

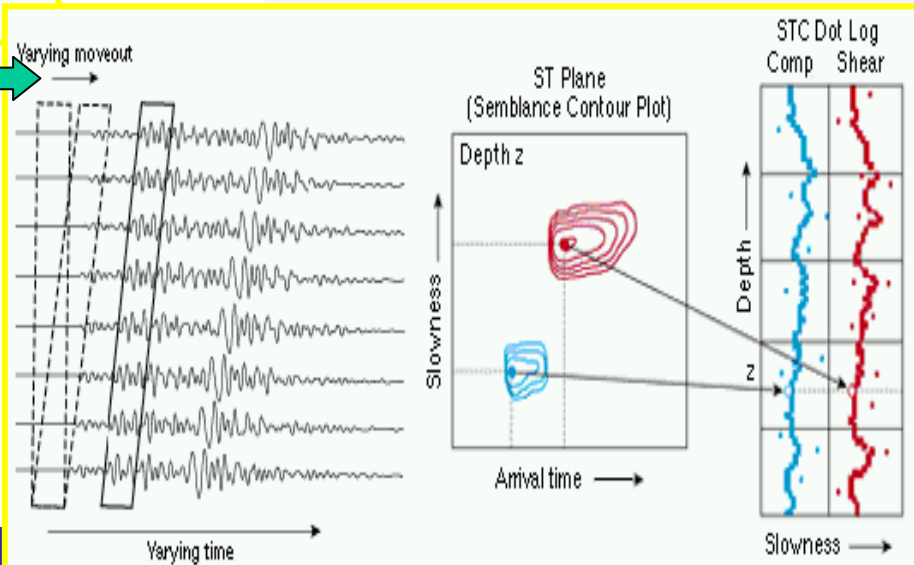
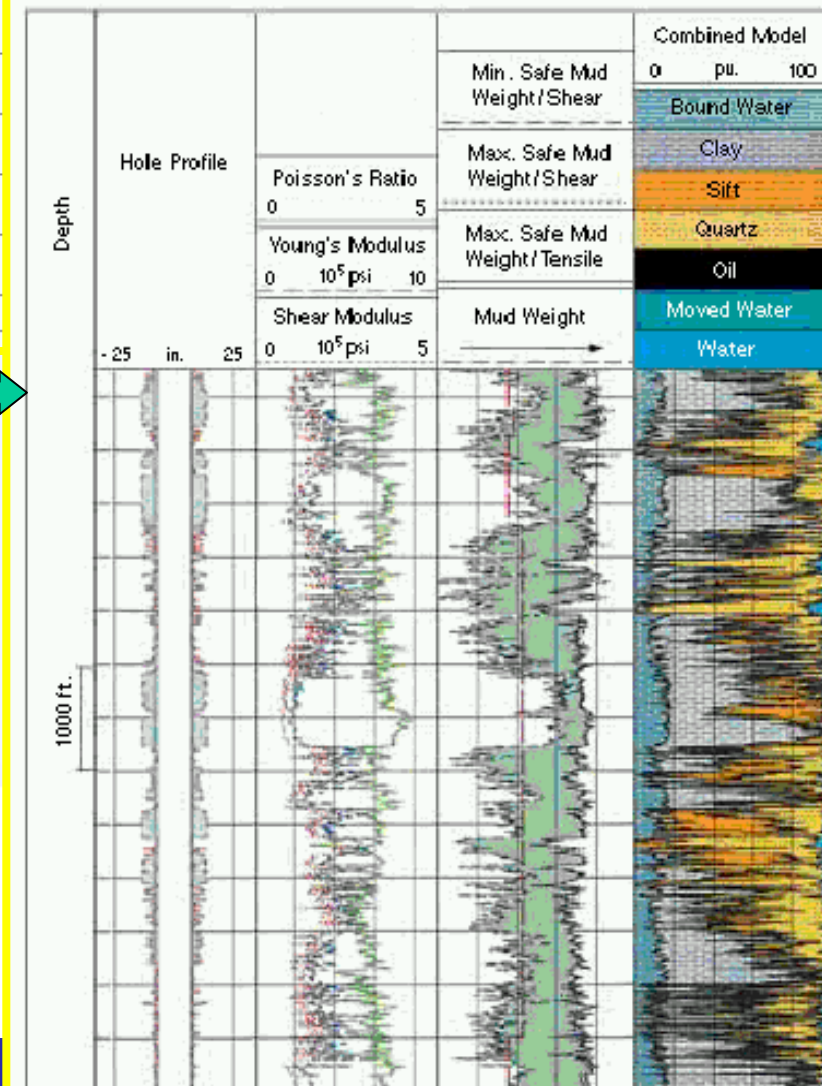


Well Logs: "rock mechanics"



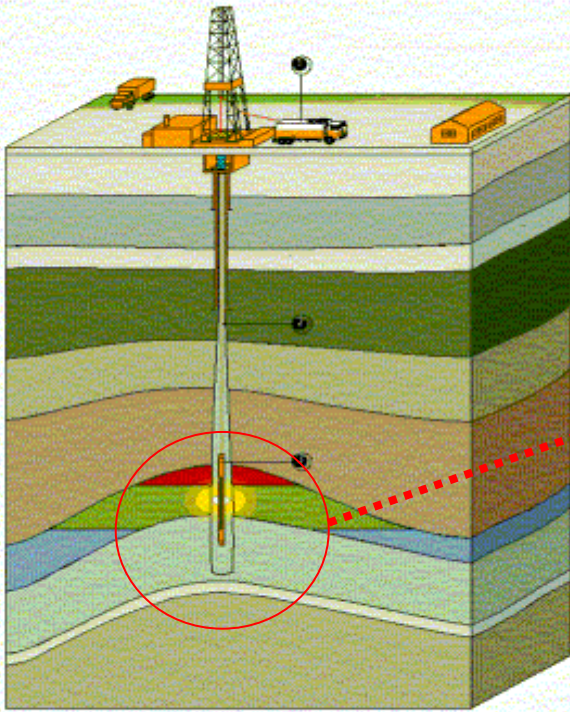
ν	Poisson's ratio	$\frac{\text{Lateral strain}}{\text{Longitudinal strain}}$	$\frac{1}{2} \left(\frac{DTS}{DTC} \right)^2 - 1$
G	Shear modulus	$\frac{\text{Applied stress}}{\text{Shear strain}}$	$\frac{\rho_b}{DTS^2} \times a$
E	Young's modulus	$\frac{\text{Applied uniaxial stress}}{\text{Normal strain}}$	$2 G(1 + \nu)$
K_b	Bulk modulus	$\frac{\text{Hydrostatic pressure}}{\text{Volumetric strain}}$	$\rho_b \left(\frac{1}{DTC^2} - \frac{4}{3 DTS^2} \right) \times a$
C_b	Bulk compressibility (with porosity)	$\frac{\text{Volumetric deformation}}{\text{Hydrostatic pressure}}$	$\frac{1}{K_b}$

Note: Coefficient $a = 1.34 \times 10^{10}$ if ρ_b in g/cm³ and DT in μ sec/ft.



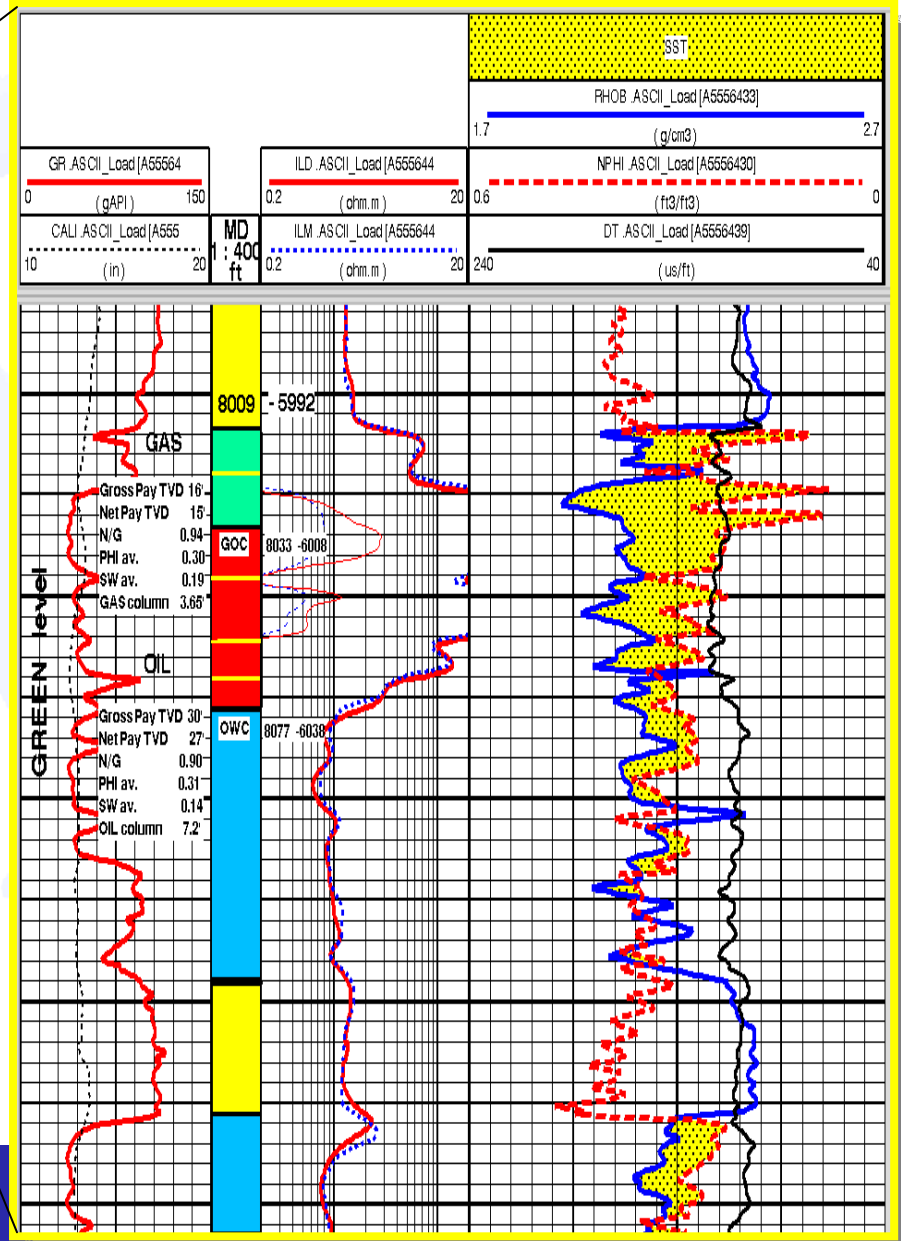
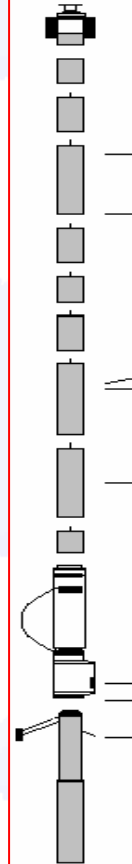
Logging While Drilling

Logging the Well



LOGGING OPERATION

- Logging Unit
- Conductor Wireline
- Logging Instrument



MWD – Measuring While Drilling

- It is a technology that allows to collect **well data in real-time**.
- The technology uses sensors and tools integrated in the BHA, close to the bit, collecting data downhole and sending them to the surface
- It is possible to measure:
 - DIRECTIONAL DATA (azimuth, hole deviation)
 - CONTROL DATA (annular temperature, weight on bit, torque)
 - CORRELATION DATA (formation radioactivity, resistivity)

LWD – Logging While Drilling

- Within the MWD technology are qualified, as LWD measurements, all the **data collected in real-time** to evaluate the reservoir petrophysical parameters **for quantitative analysis**.
- Data are sent to surface via mud-pulse telemetry for real-time evaluation and stored in the downhole memory for next retrieval.
- At present the LWD measurements available are:
 - RESISTIVITY, NEUTRON, DENSITY, PEF, SONIC, GAMMA RAY, CALIPER, MAGNETIC RESONANCE, FORMATION TESTING

LWD and WLL: different technologies with the same target

LWD

- ❖ Real-time acquisition
- ❖ Tools mounted on the BHA

WLL

- ❖ After drilling acquisition
- ❖ Tools run by means of a cable

**RESERVOIR PETROPHYSICAL
CHARACTERIZATION**

WLL ADVANTAGES

- Logging speed controlled
- Very well known technology
- High speed of data transmission
- Large choice of different tools

WLL DISADVANTAGES

- High rig time costs
- Measurements after invasion and wash out

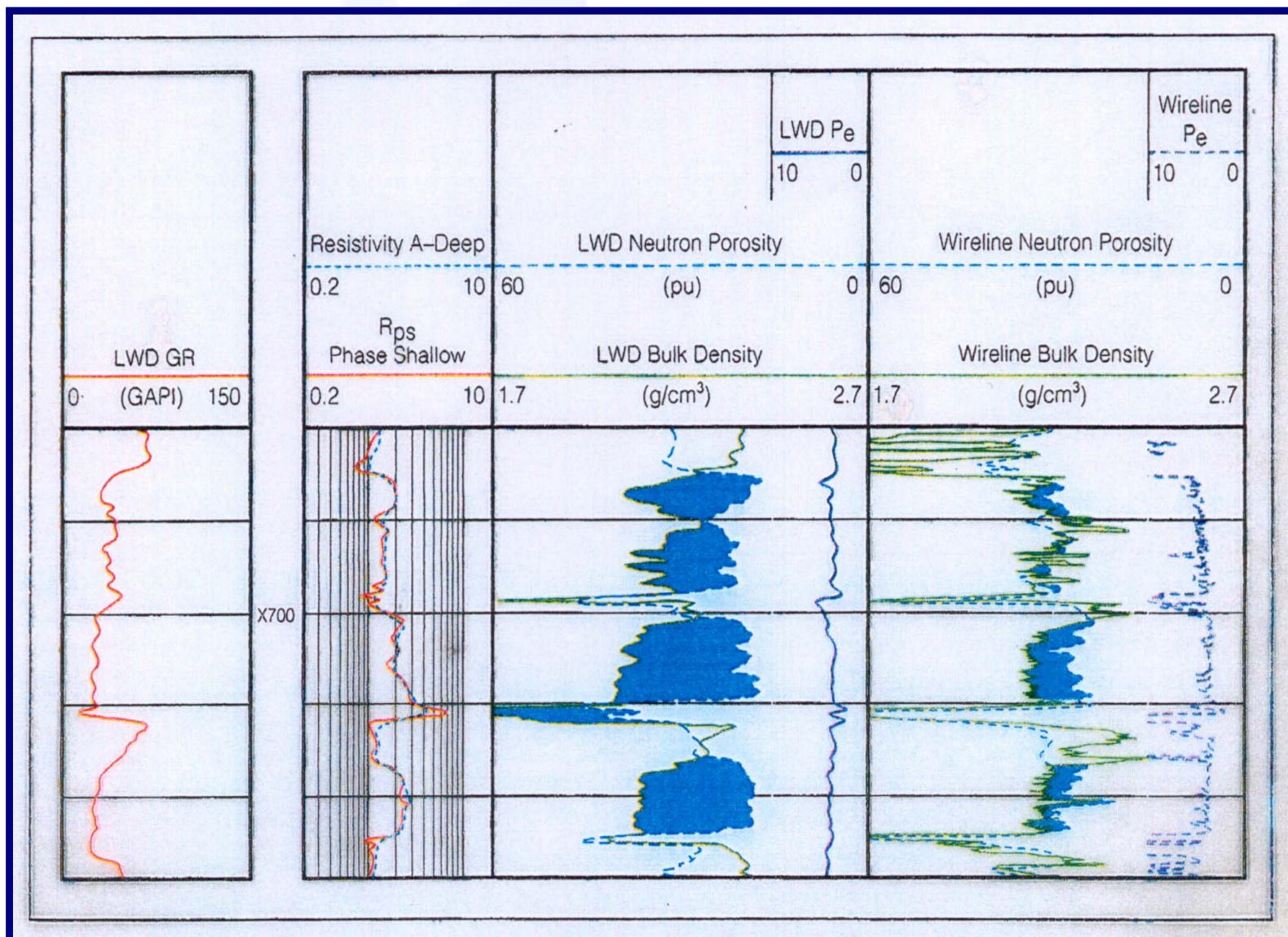
LWD ADVANTAGES

- Quick operational decisions
- Real-time drilling information (for csg. Shoe, correlation, coring point, pore pressure determination, etc..)
- Pre-invasion and pre-wash out data
- Insurance logging
- Rig time saving
- Geosteering

LWD DISADVANTAGES

- Low speed of data transmission
- Restricted choice of tool diameters
- New technology, not deeply known

LWD: PRE-INVASION DATA example



Gas effect on LWD neutron porosity and density, masked on VLL logs due to invasion

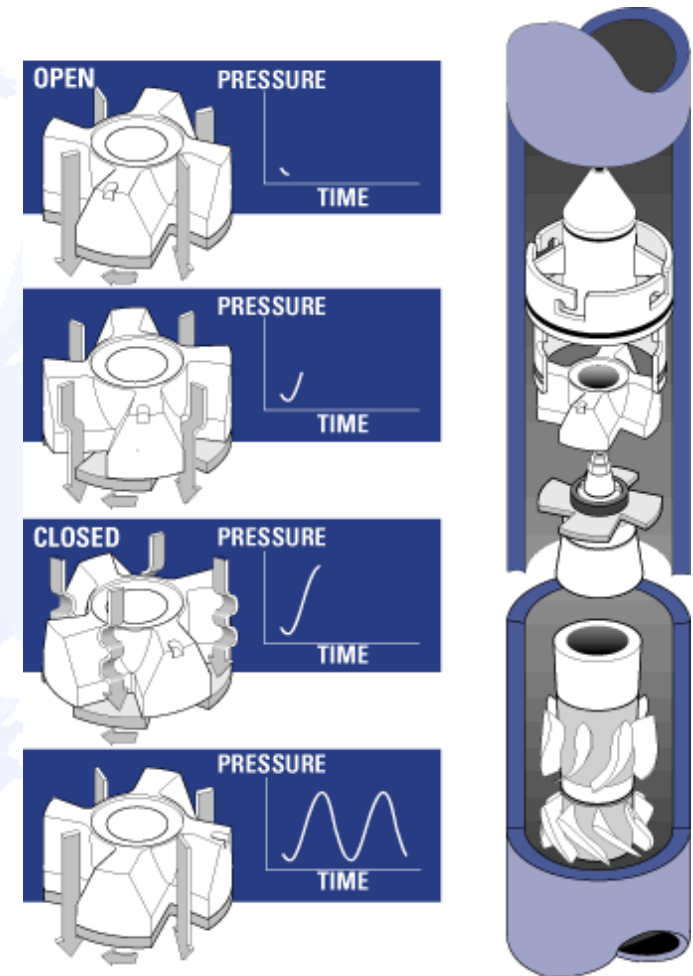
LWD ACQUISITION KEY POINTS

- ❑ **DATA TRANSMISSION** up to the surface using the “MUD PULSE” system
- ❑ **DATA STORAGE IN THE DOWNHOLE MEMORIES** (each tool has a finite memory which limits the amount of data that can be stored; if the memory fills before the end of the bit run, data will be missed)
- ❑ **THE SAMPLE RATE** must be set taking into consideration:
 - the RATE OF PENETRATION (sample rate and rate of penetration determine the data density versus depth)
 - the length of the BIT RUN

The sampling rate must be selected for each bit run to match the conditions anticipated and to be adequate for the formation evaluation

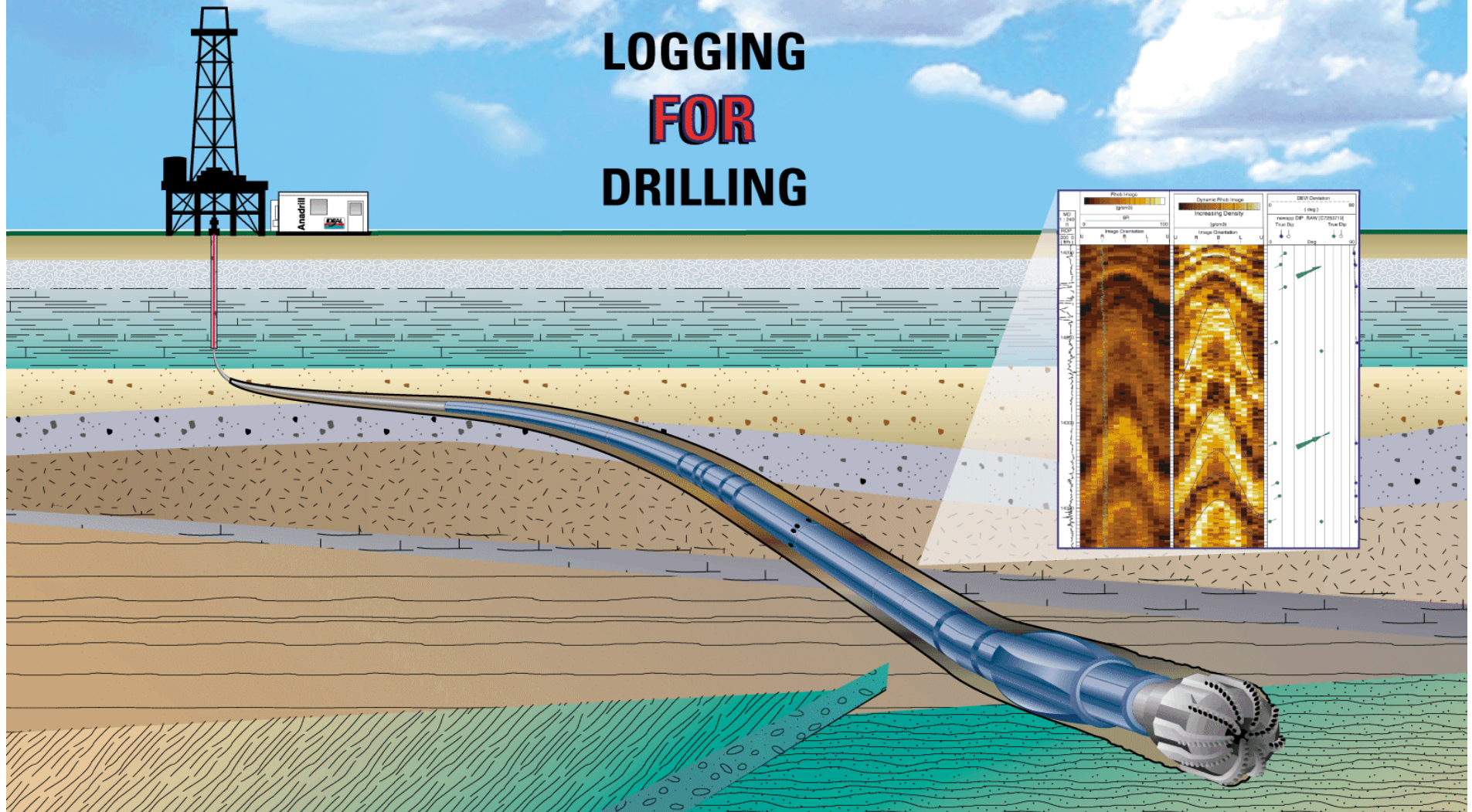
Logging While Drilling Telemetry

- In downhole tool measurement data are converted into a binary code
- In the downhole mud pulse transmitter a poppet valve moves in accordance with the code and induces a pressure pulses in the drilling mud
- Mud pulses travel through the mud and the drill string at several thousand feet per second
- At the surface the pulses are detected by a trasducer and translated into electrical signals

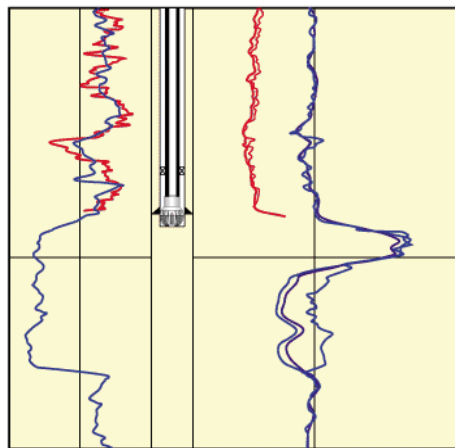
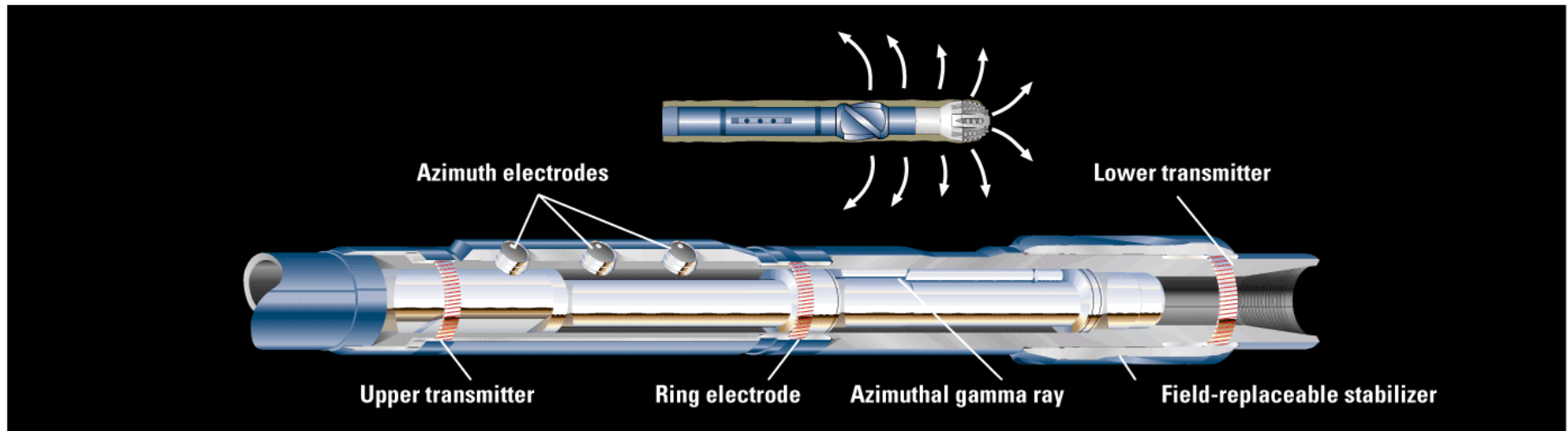


VISION Services

LOGGING
FOR
DRILLING

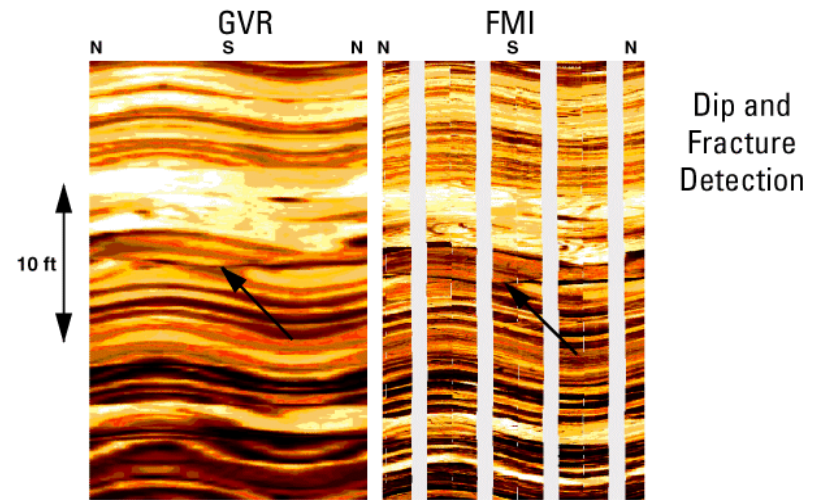


Geosteering



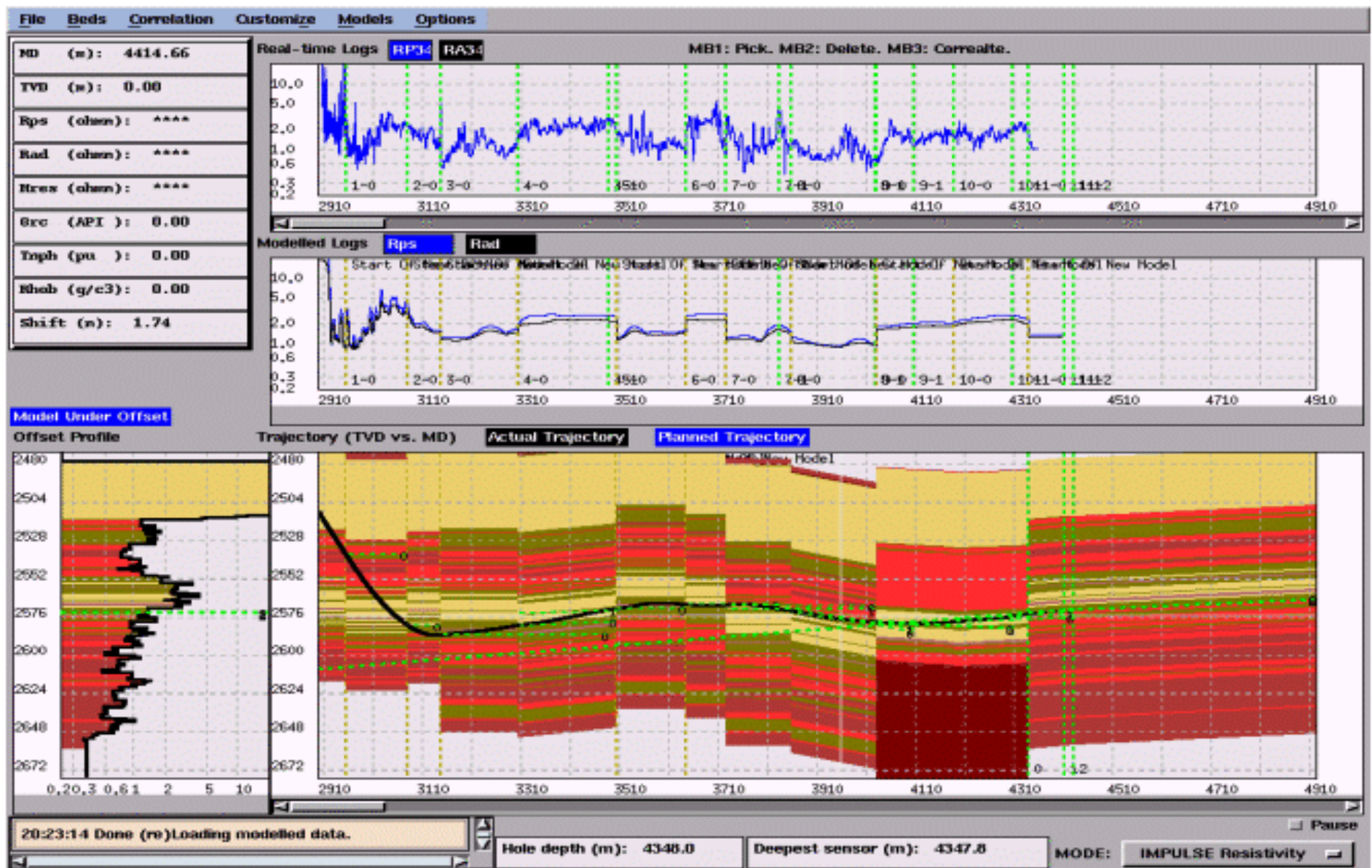
Instantaneous Casing
Point Identification

At-the-Bit Resistivity



Dip and
Fracture
Detection

Geosteering

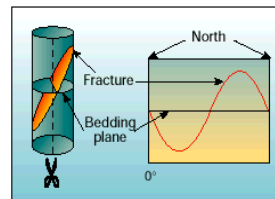


Geosteering

SSE

High dips in fault
Expected Fault

Vertical Well



Horizontal Well

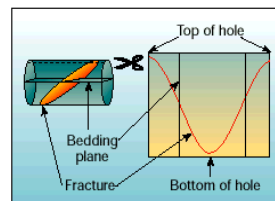
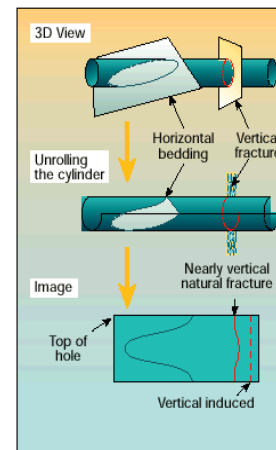
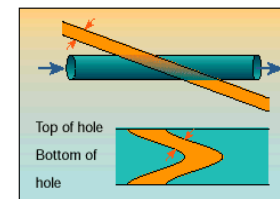


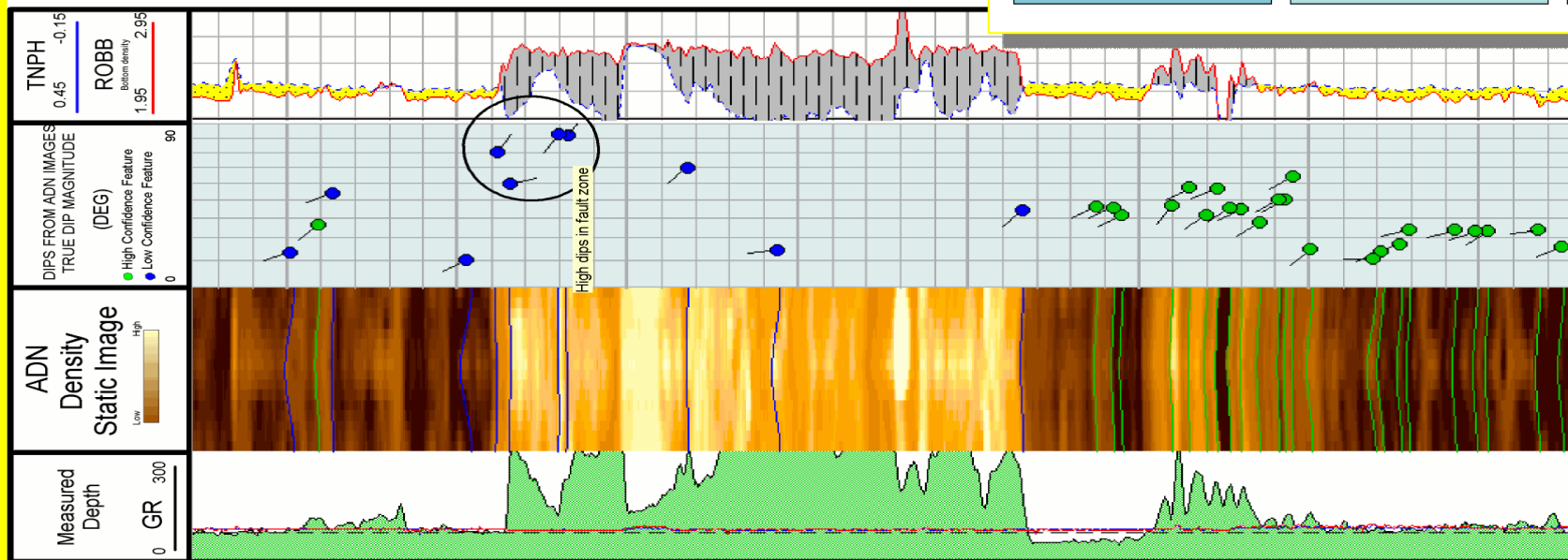
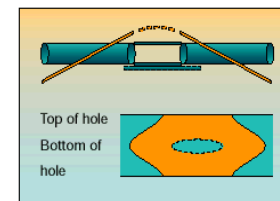
Image in Horizontal Hole



Bed Dipping Away from Kickoff Point



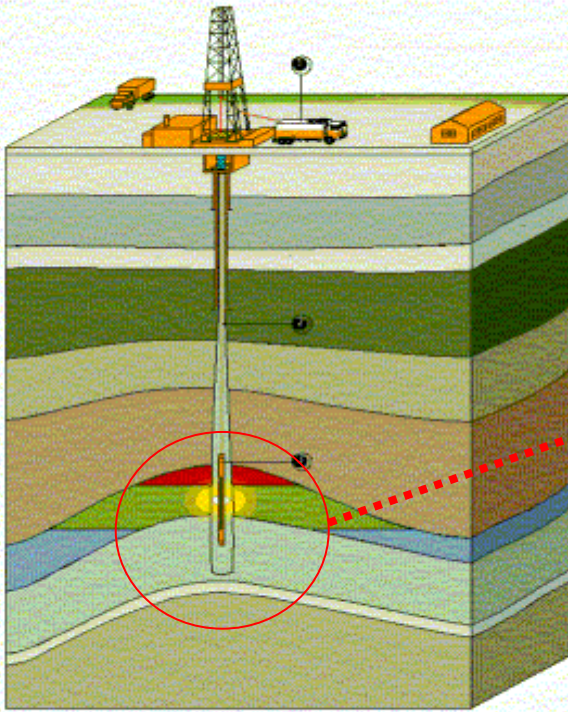
Folded Bed



300 feet

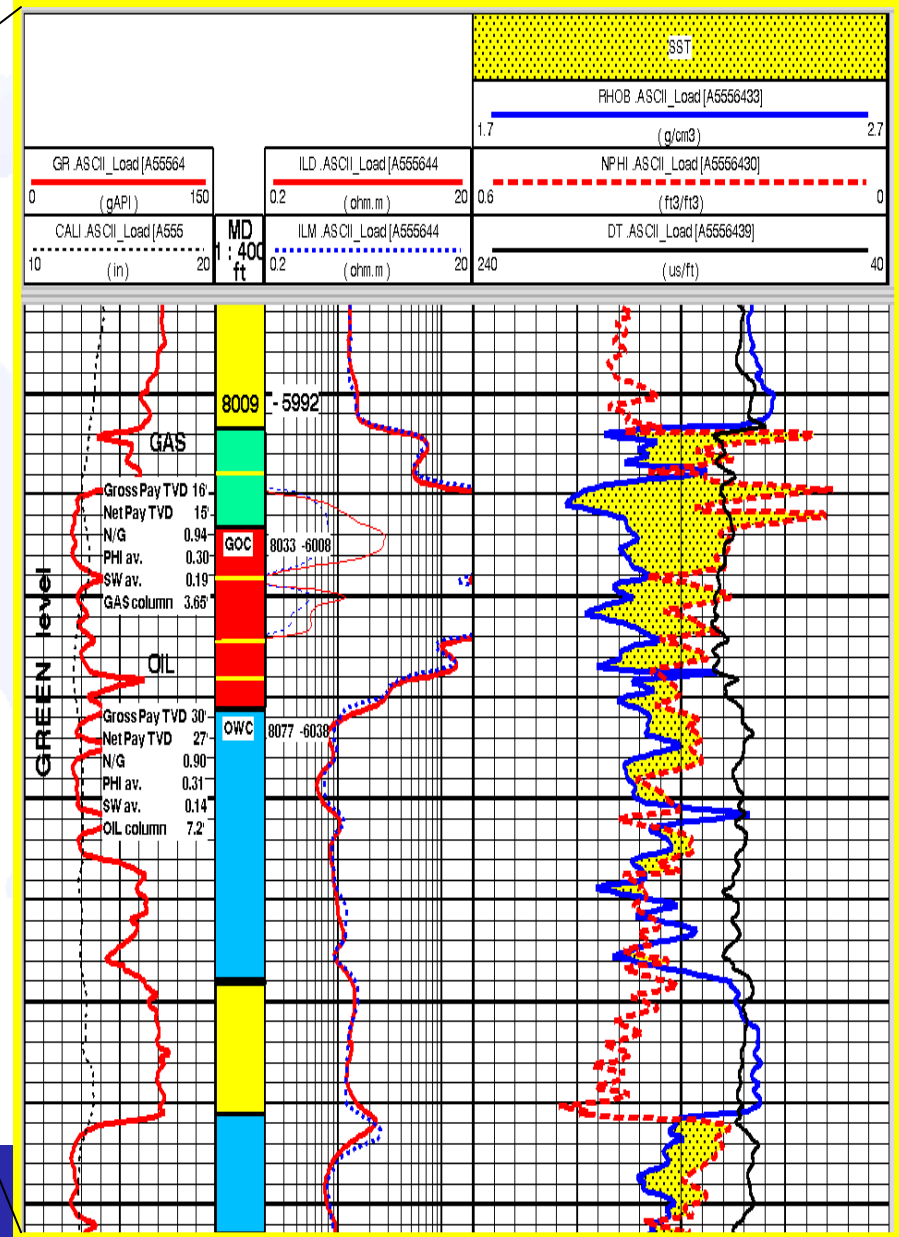
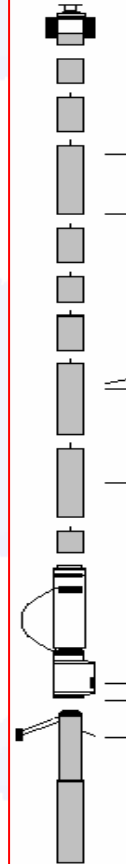
Logging Cased Hole

Logging the Well

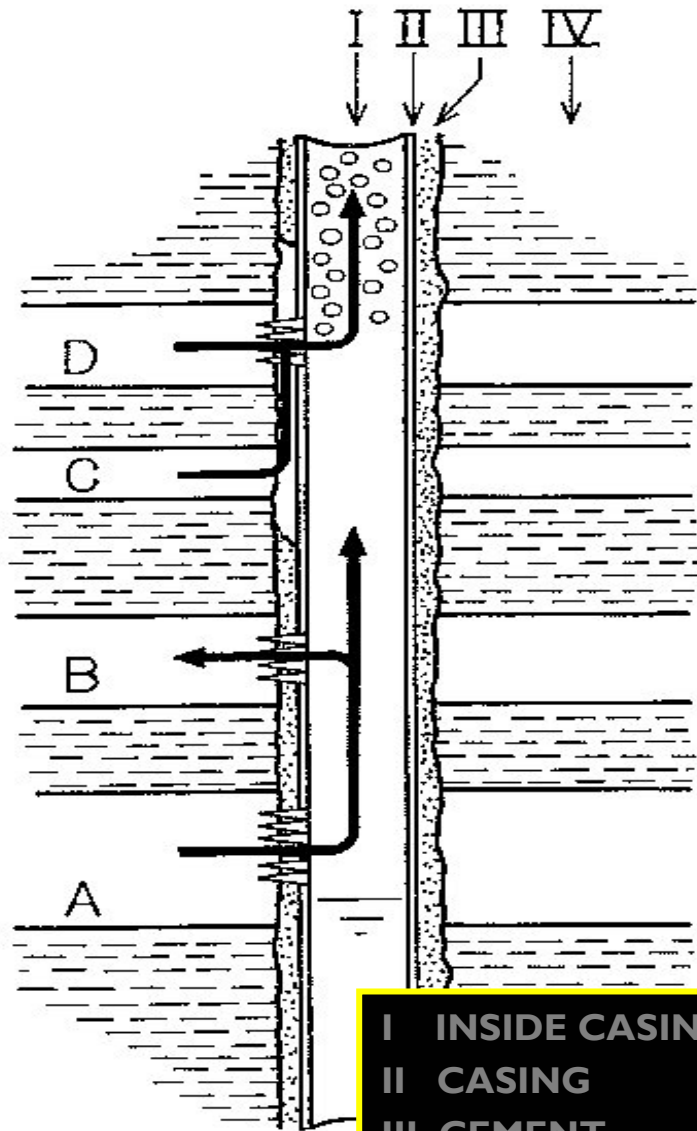


LOGGING OPERATION

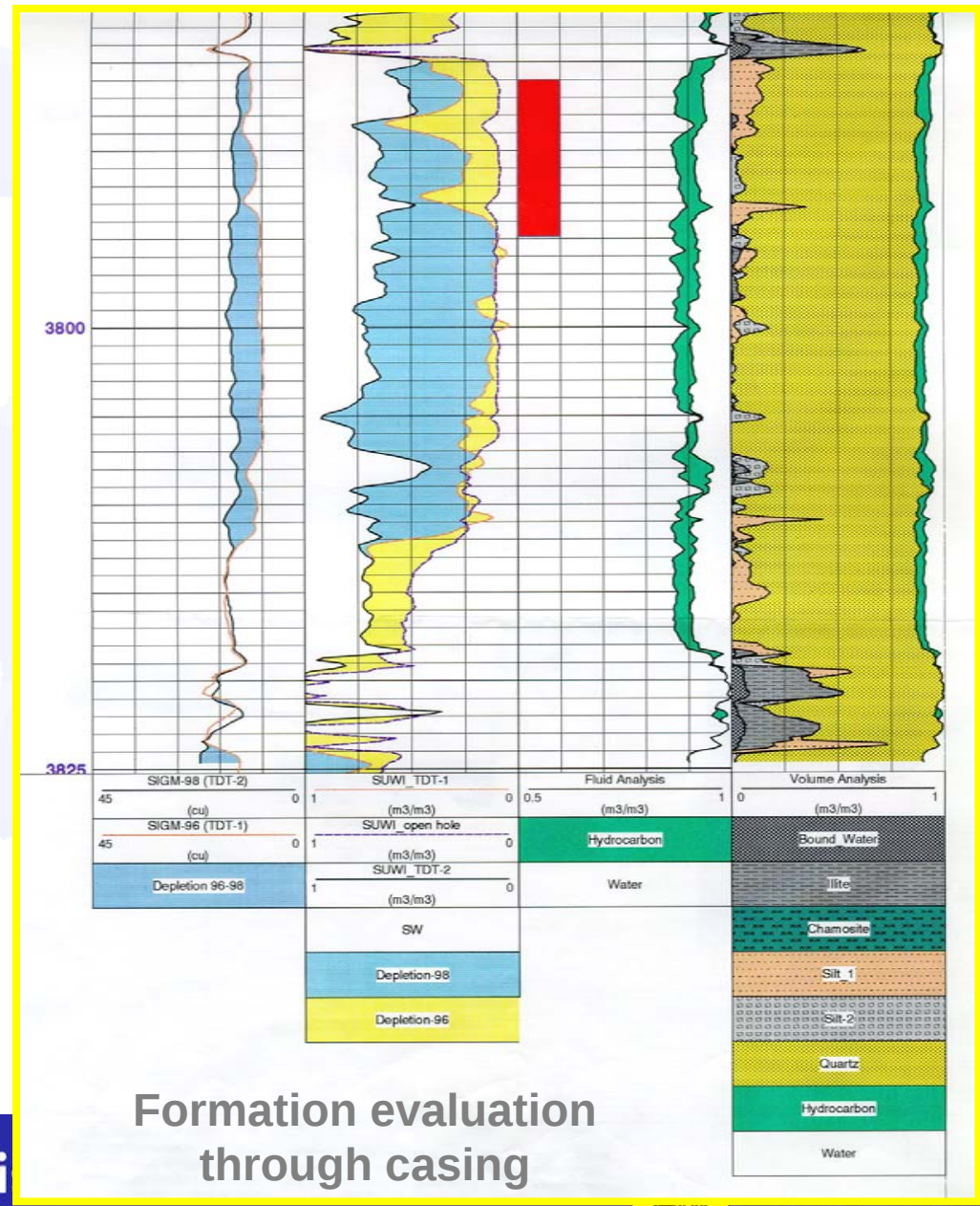
- Logging Unit
- Conductor Wireline
- Logging Instrument



Cased Hole Logging



I INSIDE CASING
II CASING
III CEMENT
IV FORMATION



Formation evaluation
through casing

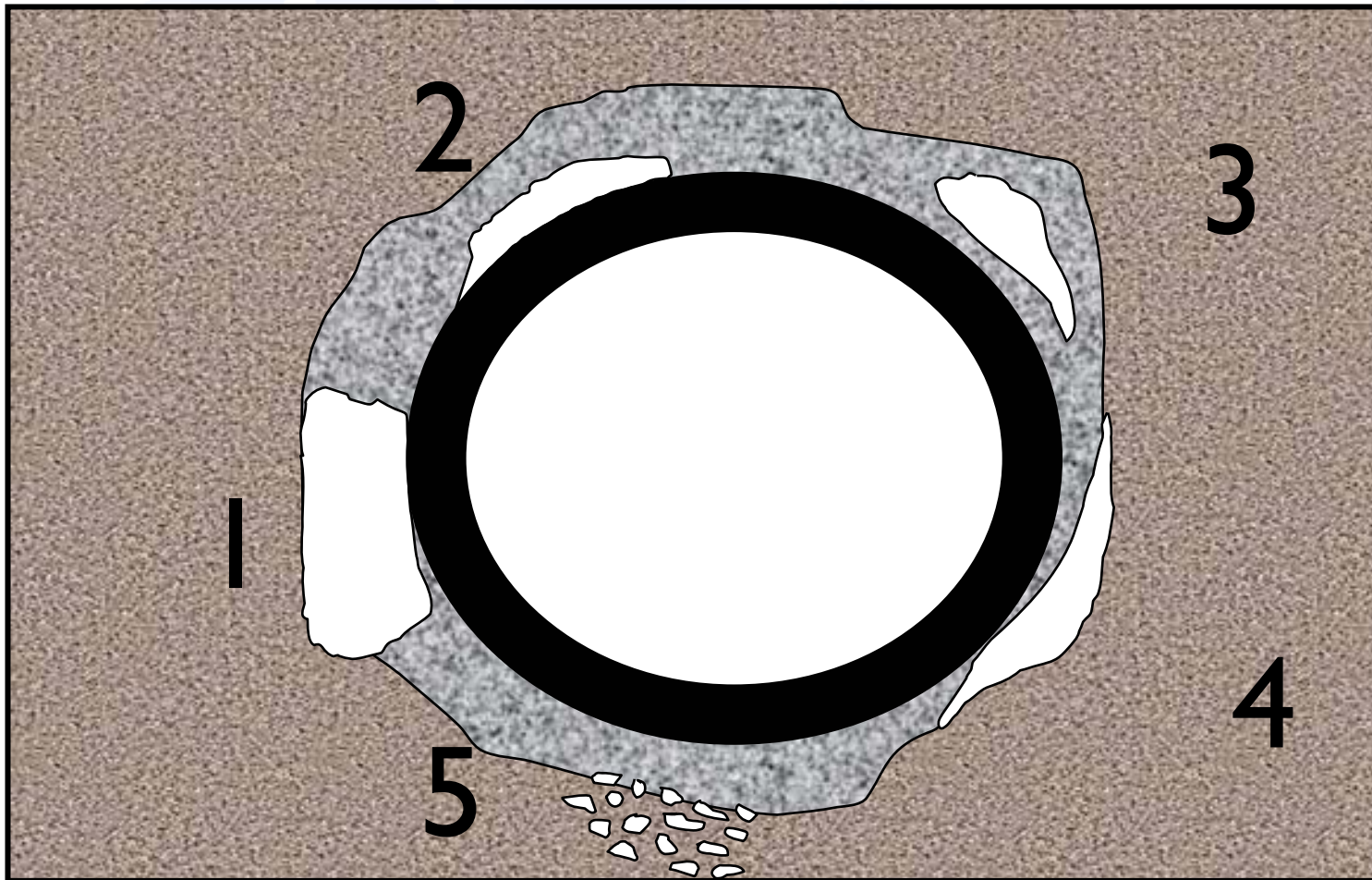
Casing

- The casing is a steel pipe cemented in place in an oil or gas well as the drilling progresses or when the well is completed.
- The casing serves several purposes:
 - (1) to prevent the formation walls from caving or squeezing into the hole during drilling
 - (2) to protect one formation from damage when heavy mud weights are required in drilling another
 - (3) to provide a means to isolate porous and permeable formations at the wellbore
 - (4) to prevent contamination of shallow aquifers by drilling muds.

Why to cement the casing ?

- To fill the annulus between the casing and formation with cement to support the casing, improve zonal isolation and to prevent migration of fluids between permeable zones.
- A Cement Evaluation log is run, in the cased interval, in order to evaluate the cement bond

Cement Channels



Cement Bond Log (CBL)

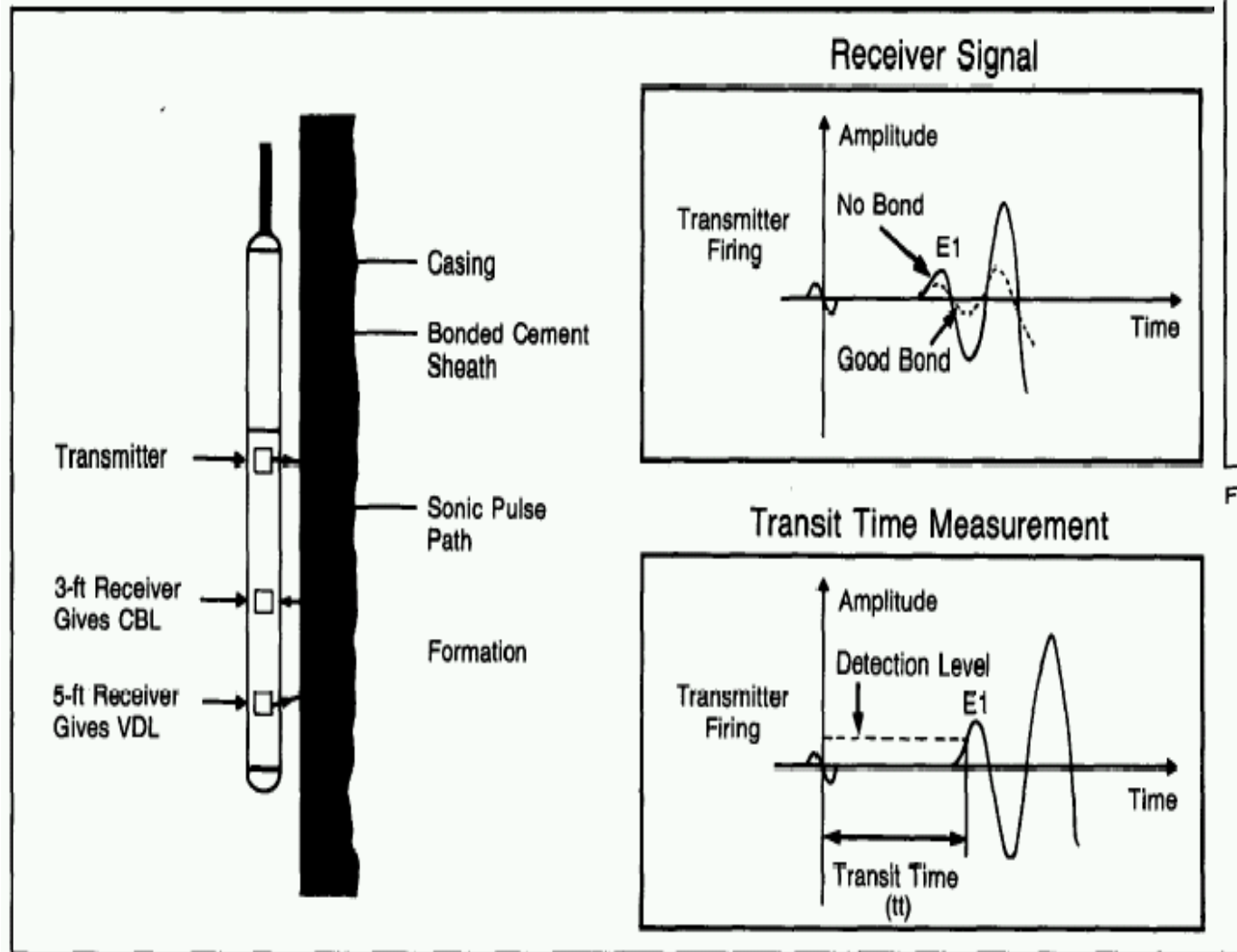


Fig. 5-3—CBL measurement

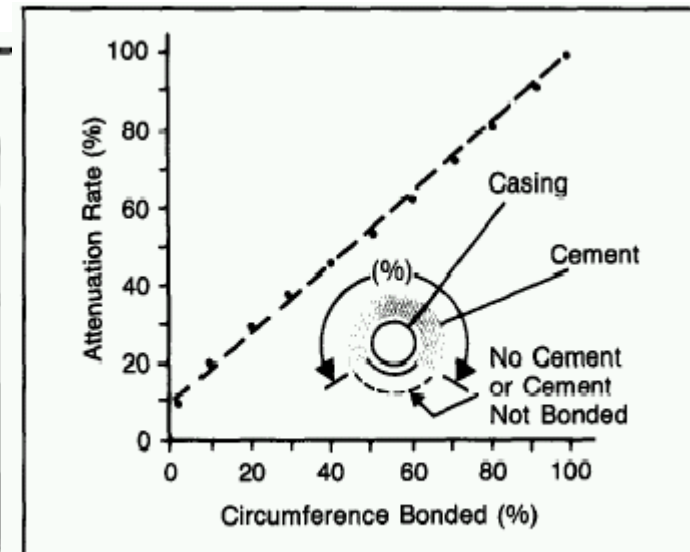
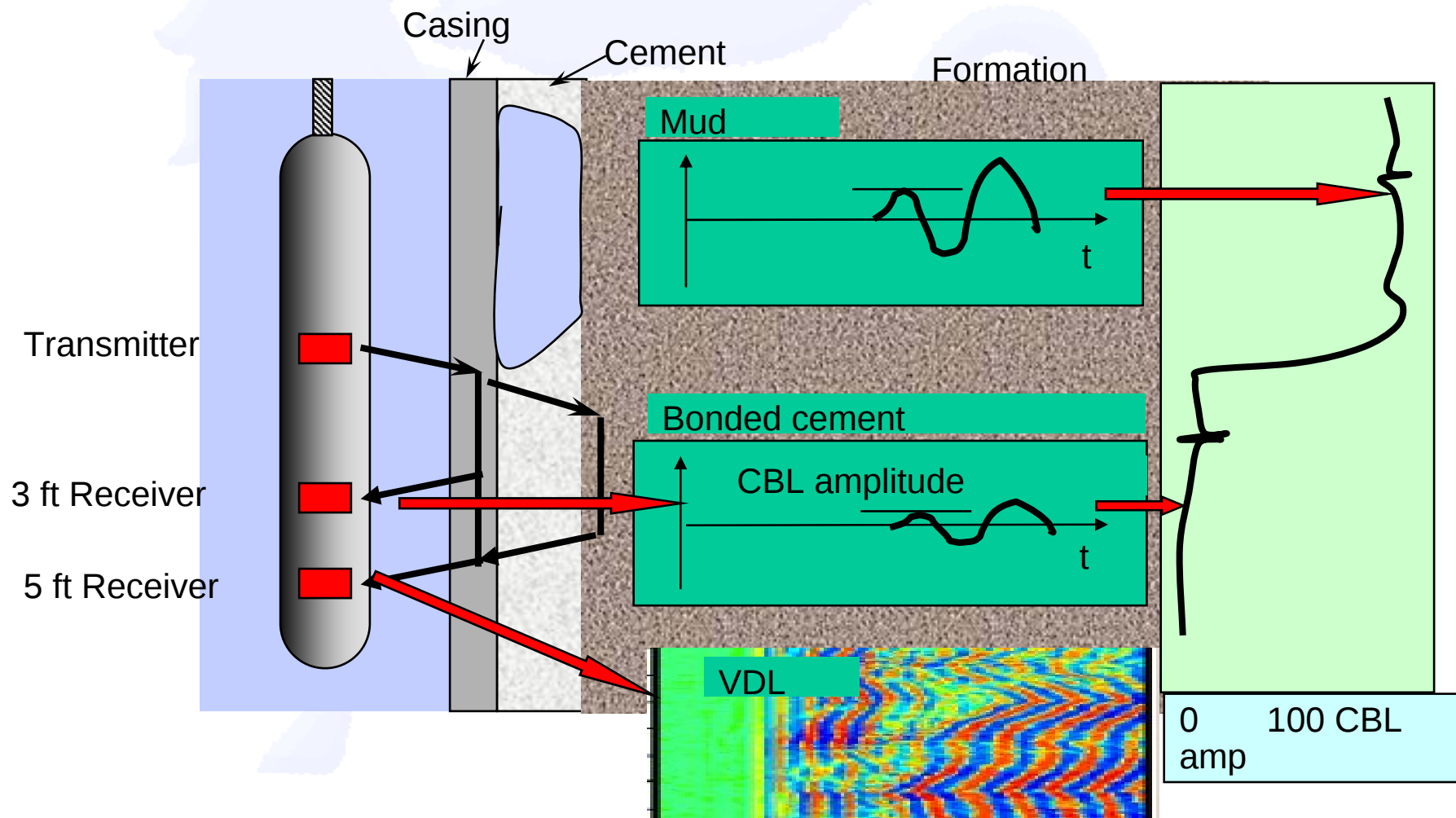
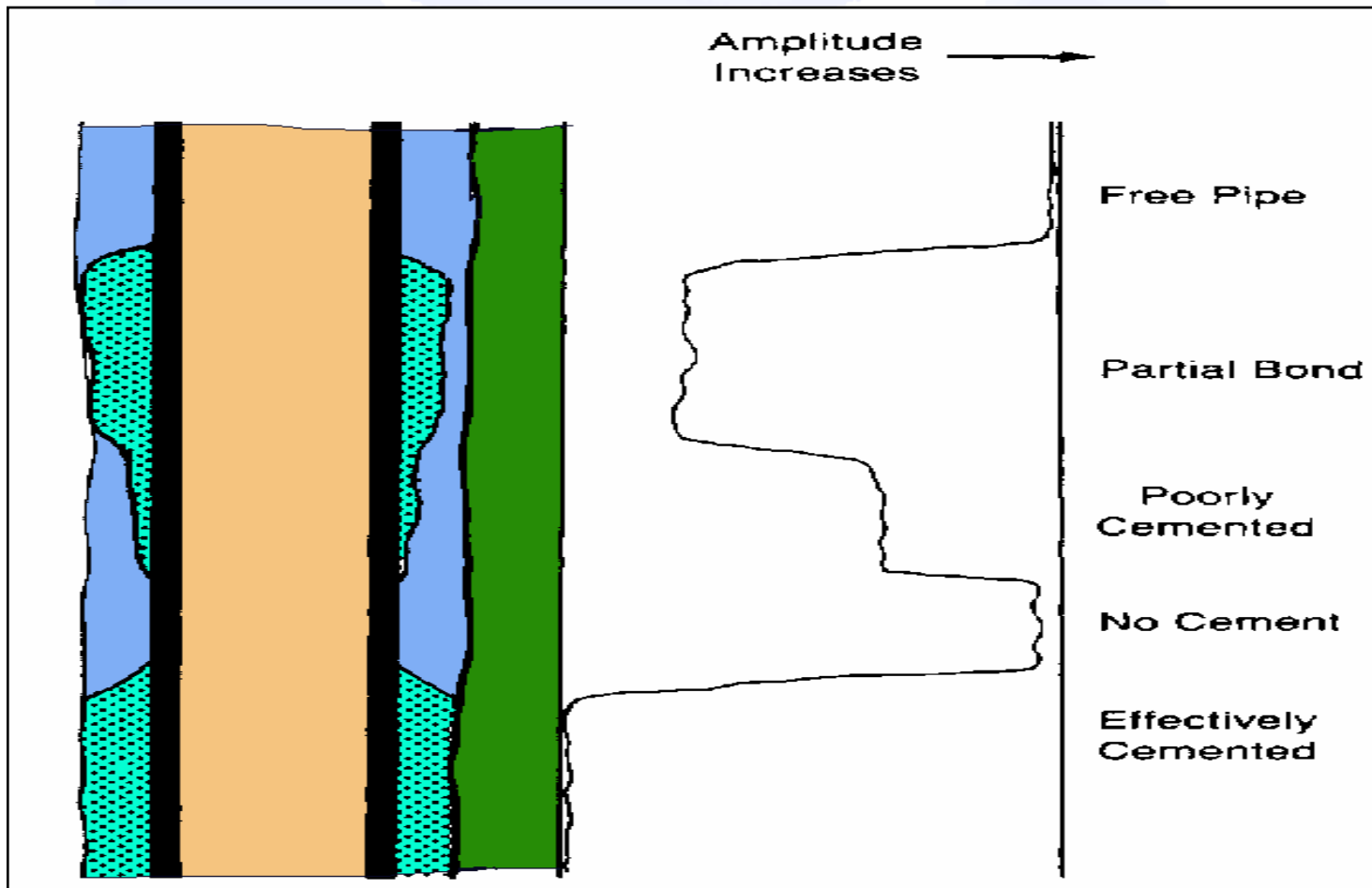


Fig. 5-4—CBL tool response in channels

Sonic (CBL / VDL) principle



CBL : qualitative interpretation of the Amplitude curve



Cased Hole Logging: TDT

The Thermal Decay Log (TDT) is based on the capture capacity of the thermal neutrons:

Chlorine is a great thermal neutron absorber, therefore the TDT measurement is practically proportional to the quantity of water in the formation (S_w).

The following parameters must be considered during the interpretation process:

- formation water salinity;
- porosity;
- shale volume.

The main measurement is the decay time (τ), which is the input to evaluate the capture coefficient (Σ) proportional to the S_w ($\Sigma = K/\tau$).

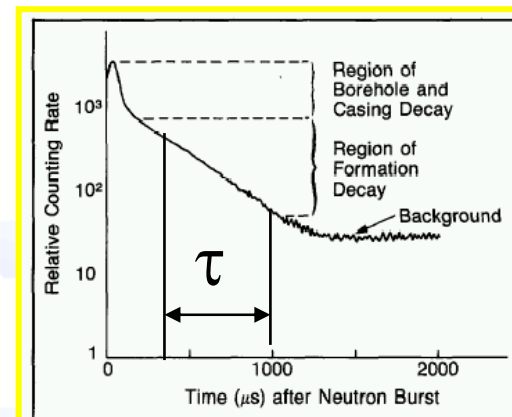
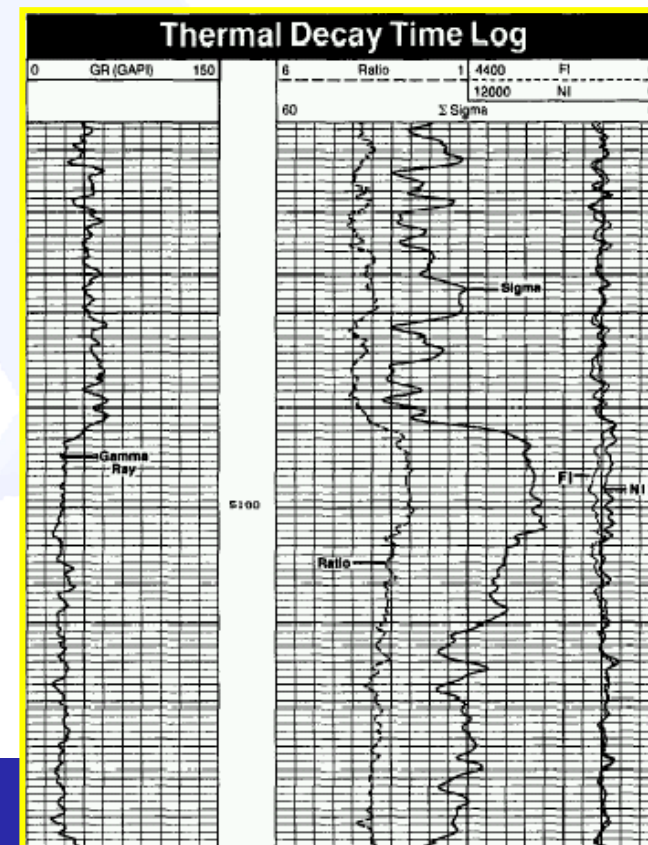
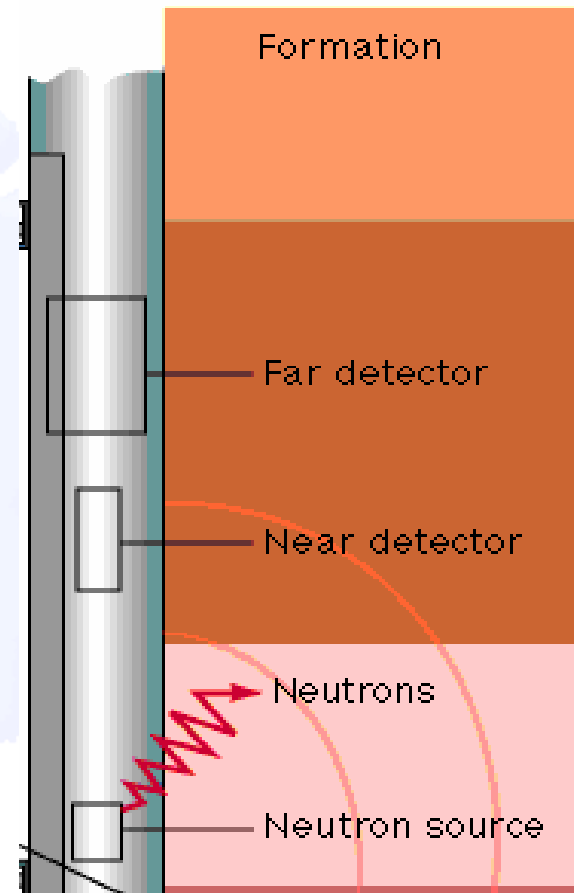


Fig. 3-18—Decay of capture gamma ray counting rate



Sigma - Principle of Measurement

- RST emits regular pulses of fast neutrons and measures the rate at which thermal neutrons are captured.
- The decrease in thermal neutron population is mainly due to neutron capture. When thermal neutrons are captured, gamma-rays are created and detected by the RST detectors.
- The rate of capture is sigma log output, mainly related to the amount of chlorine in the measurement envelope
- Borehole sigma and diffusion interfere with the simple measurement of formation sigma



PULSED NEUTRON CAPTURE

Principles of the measurement

- The source emits bursts of fast neutrons into the borehole with energy of 14 MeV.
- Neutrons collide with atoms, mainly Hydrogen, losing energy and velocity and reaching the following stages:

EPITHERMAL STAGE	$0.1 < eV < 100$
THERMAL STAGE	.025 eV

- Thermal neutrons continue colliding with other atoms, keeping average energy constant (DIFFUSION STAGE)

PULSED NEUTRON CAPTURE

Principles of the measurement

- Thermal neutrons are finally captured by some nuclei, mainly **Chlorine** and Boron. Capture Gamma Rays are then emitted.
- PNC, by detection of the emitted Gamma Rays, measures the **exponential rate** of the thermal neutron population around the tool after each burst.
- The measurement is mainly affected by the amount of formation **salty water**, because Chlorine is a strong neutron absorber.

PULSED NEUTRON CAPTURE

Principles of the measurement

- The neutron decay rate is a direct function of **CHLORINE** concentration in the formation water.
- The main output curve of PNC measurement is Σ (Formation bulk capture cross section, c.u.)

Sigma

[Cl]



than Sigma is HIGH if [Cl] is HIGH

- [Cl] is function of

Salinity of formation water

Volume of water

Φ

Sw

PULSED NEUTRON CAPTURE

Principles of the measurement

Low Σ



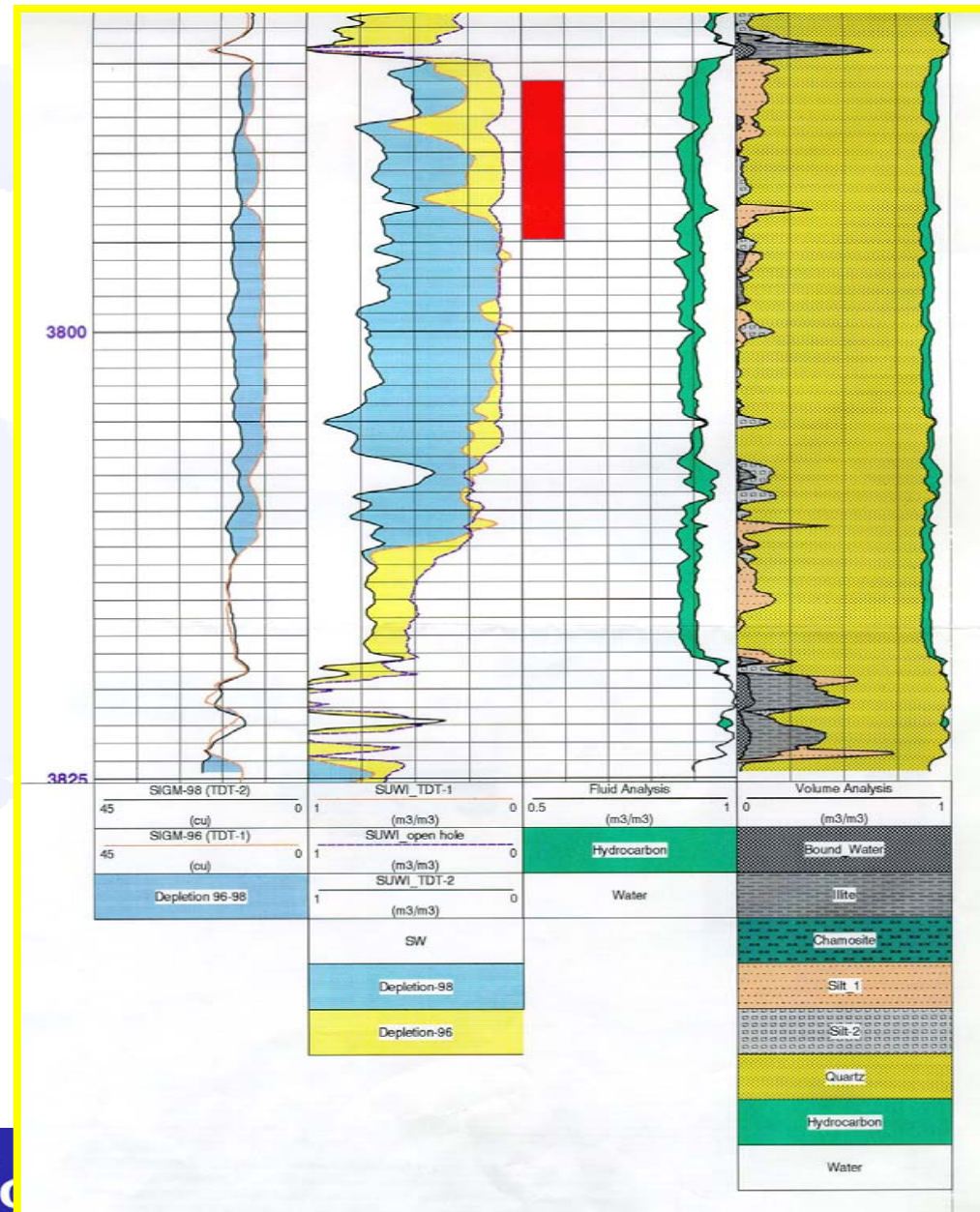
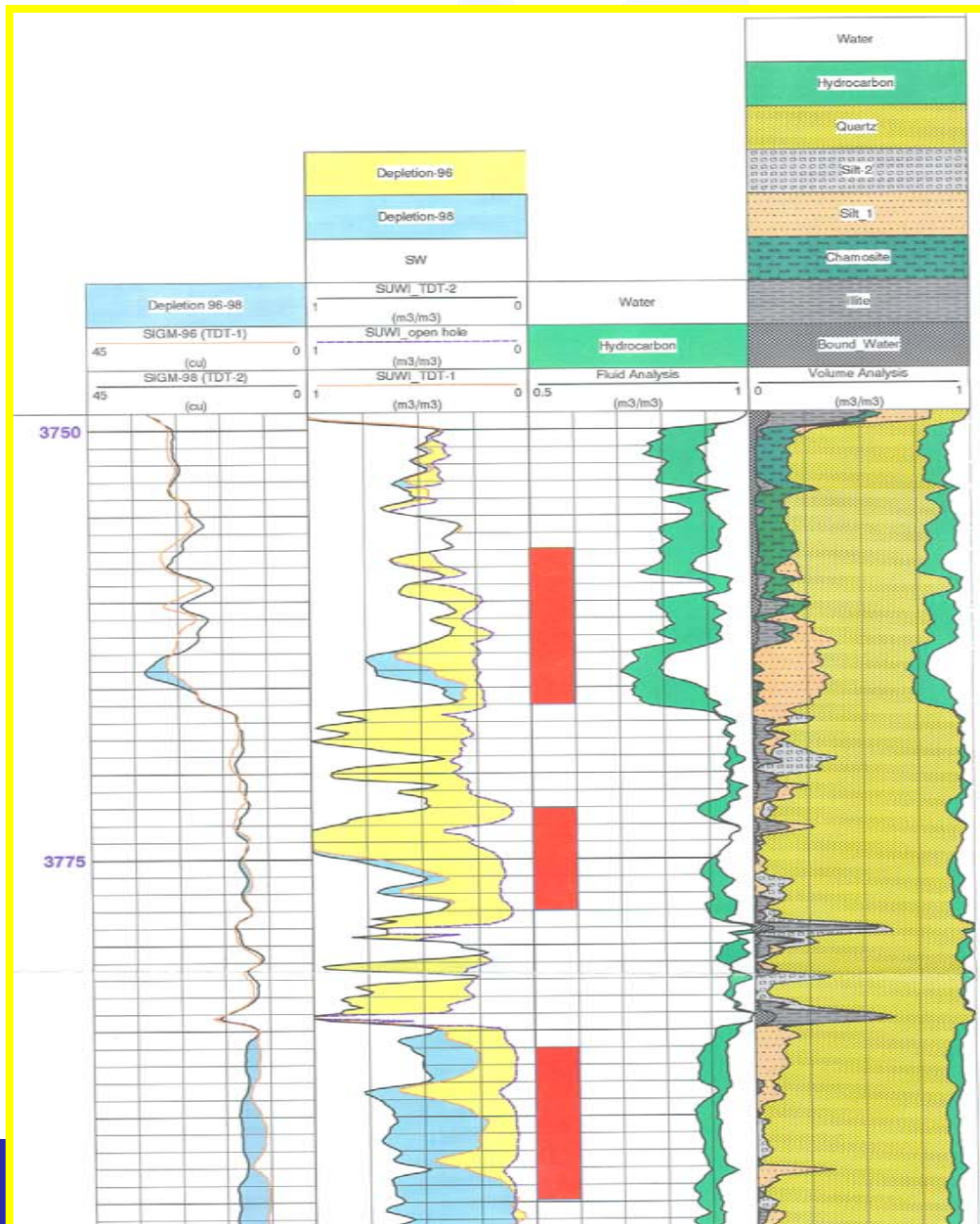
Low Porosity
Fresh Water
Low S_w

High Σ



High Porosity
High Water Salinity
High S_w

Cased Hole Logging Interpretation: CRA



Other Logs in Cased Hole applications:

- **PERFORATIONS**
- **PRODUCTION LOGS**
- **CORROSION**
- **GRAVEL PACK LOG**

Perforations

To perforate the casing the correlation logs are:

- GR or Spectral GR;
- Neutron log;
- CCL

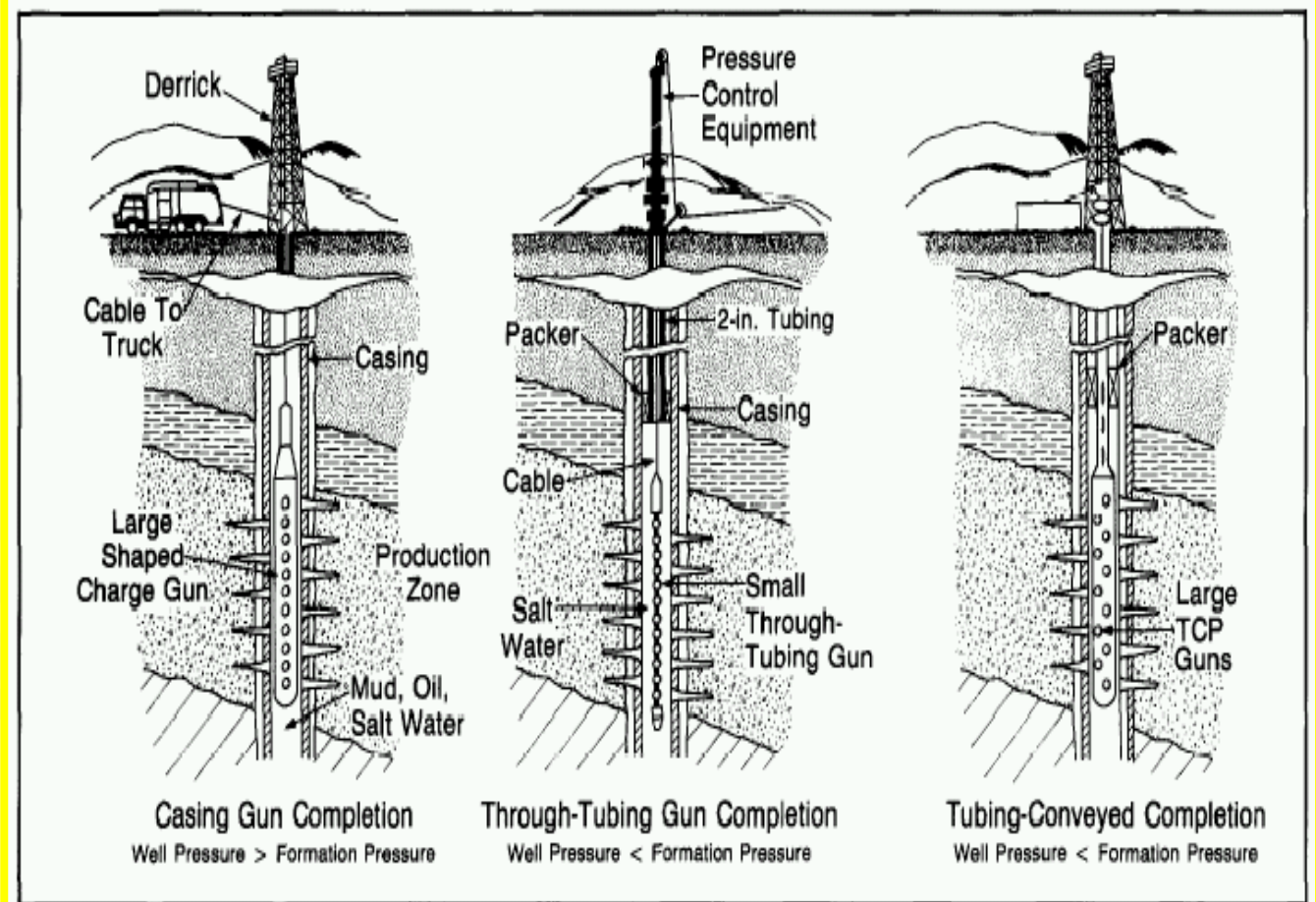
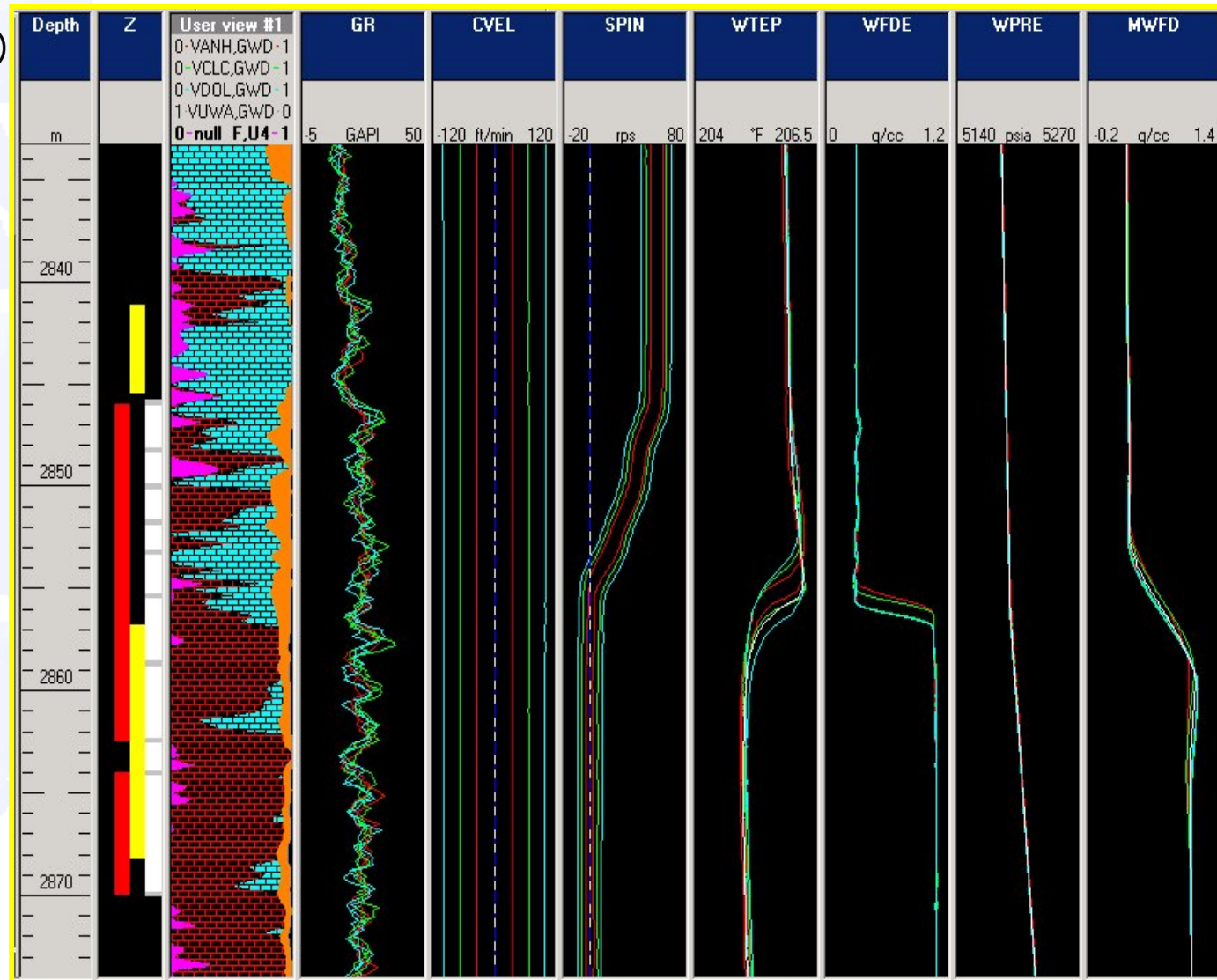


Fig. 7-29—Well completion techniques

Production Log

PSP (Production Service Platform)

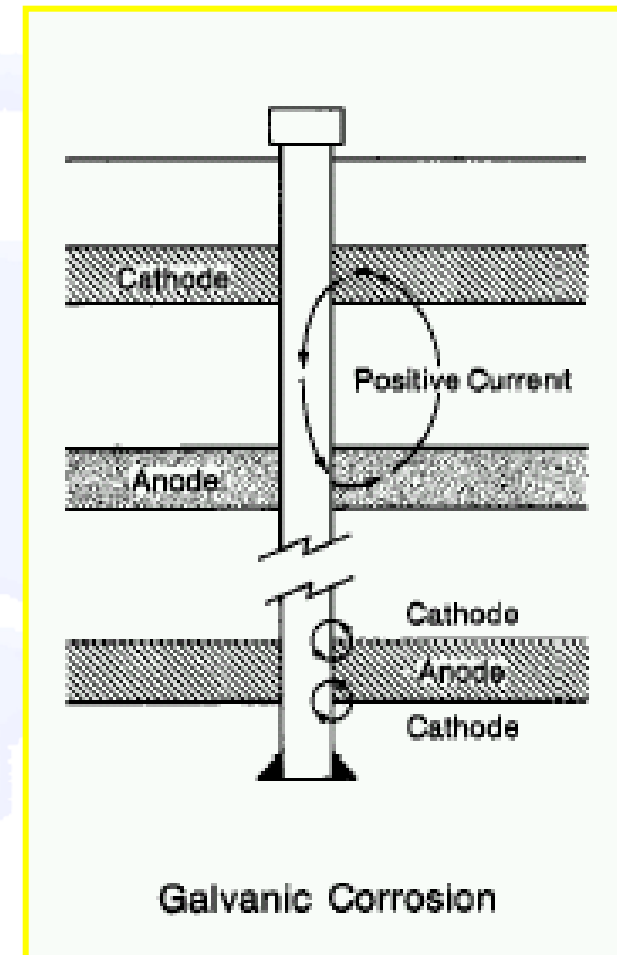
- FULLBORE SPINNER (2.5 ")
- GRADIOMANOMETER
- THERMOMETER
- MANOMETER
- GR
- CCL
- CALIPER



Corrosion

Origin

- electrochemical
 - contact of metals with formation water;
 - metal in contact with different fluids (pH, salinity and dissolved gas);
- mechanical abrasion (solids);
- Deformations due to stress in situ

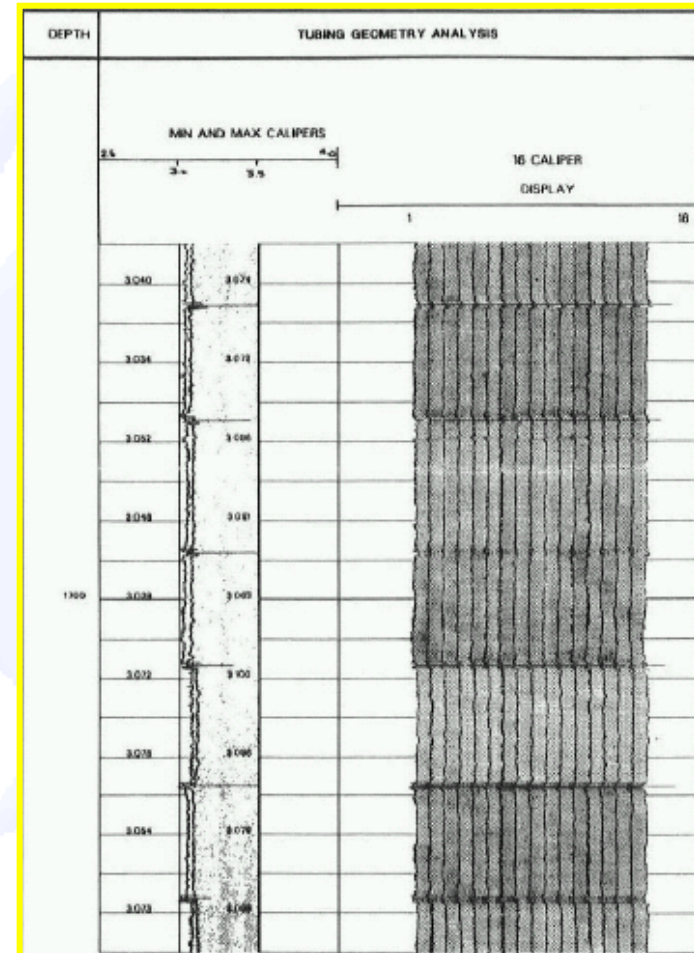


Corrosion

Corrosion monitoring

The measurements are in “time lapse” in comparison with runs at different times, and consist of the evaluation of the metal losing and thickness variation of the casings through:

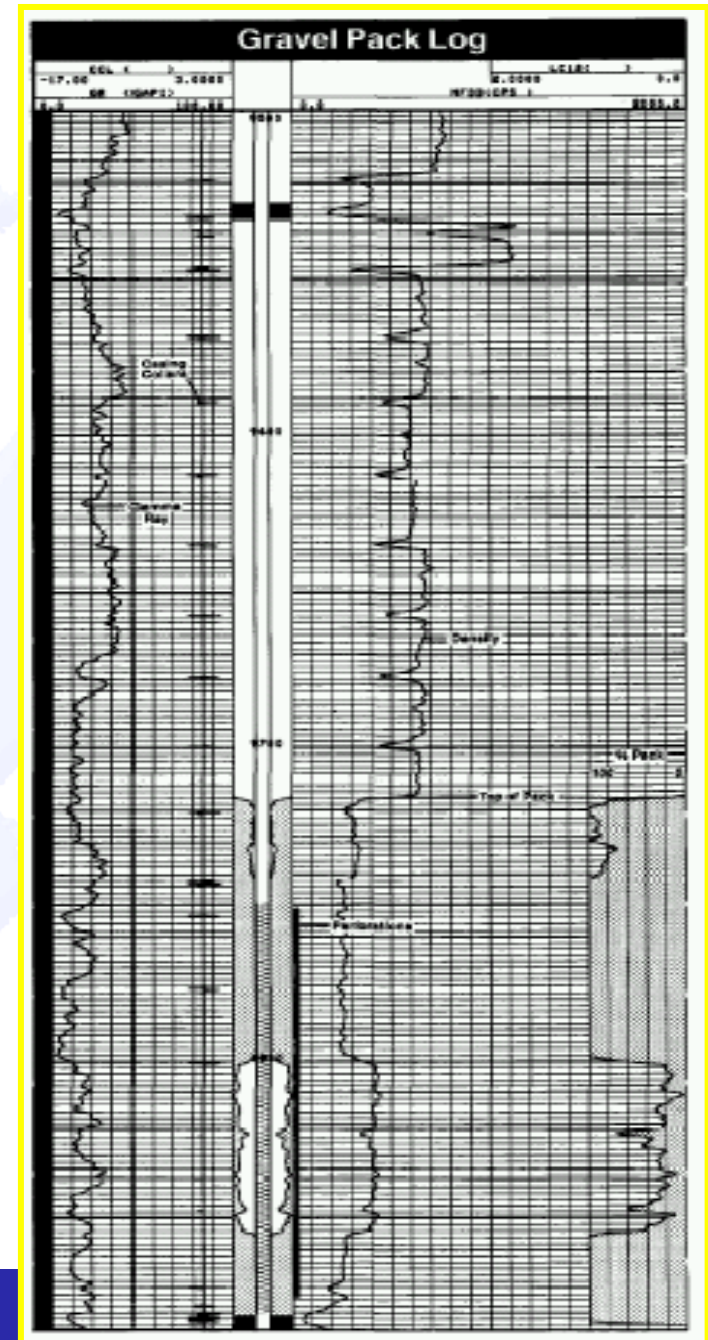
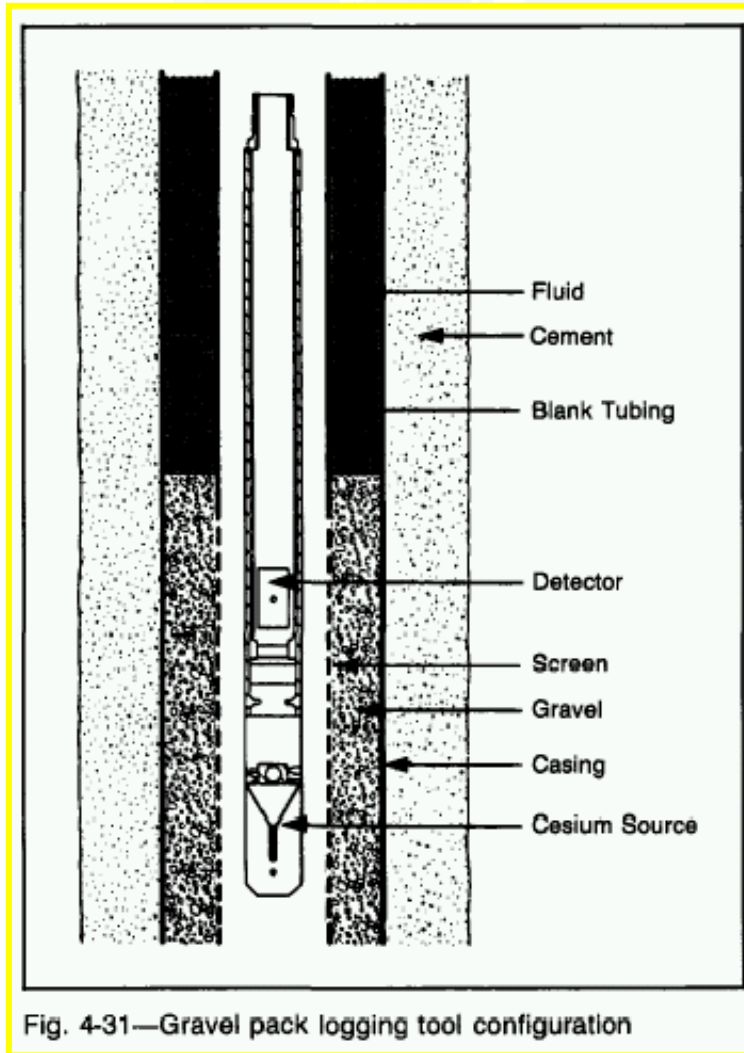
- mechanic caliper (multifinger caliper);
- acoustic caliper (BHTV);
- electromagnetic measurements (METT);
- downhole video.



Multifinger caliper

Gravel Pack Log

It is a density log



Other Logs in Open Hole-Cased Hole applications:

- FORMATION TESTER

Wire Line Formation Testing

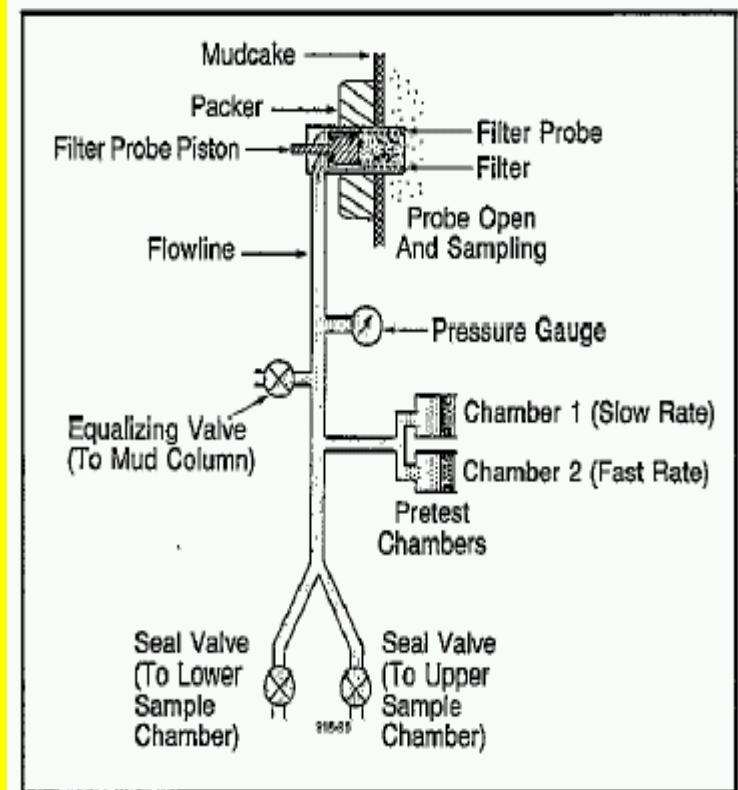
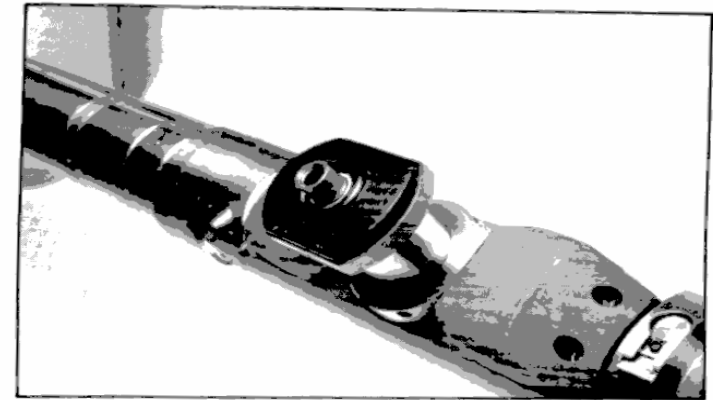
“Formation Testing” tools are generally run in Open Hole and measure:

Pressure

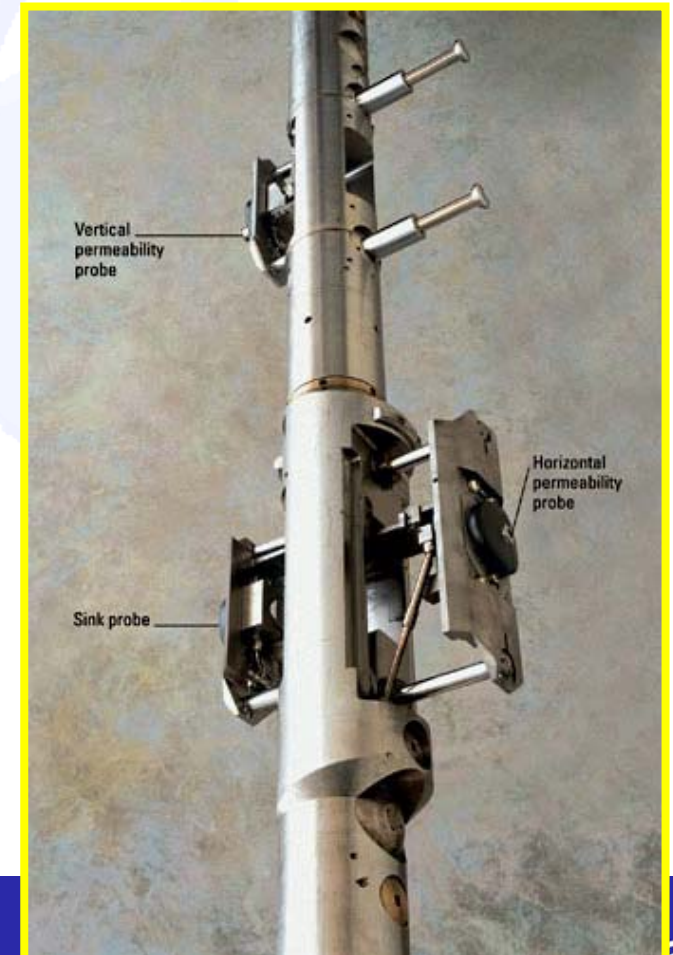
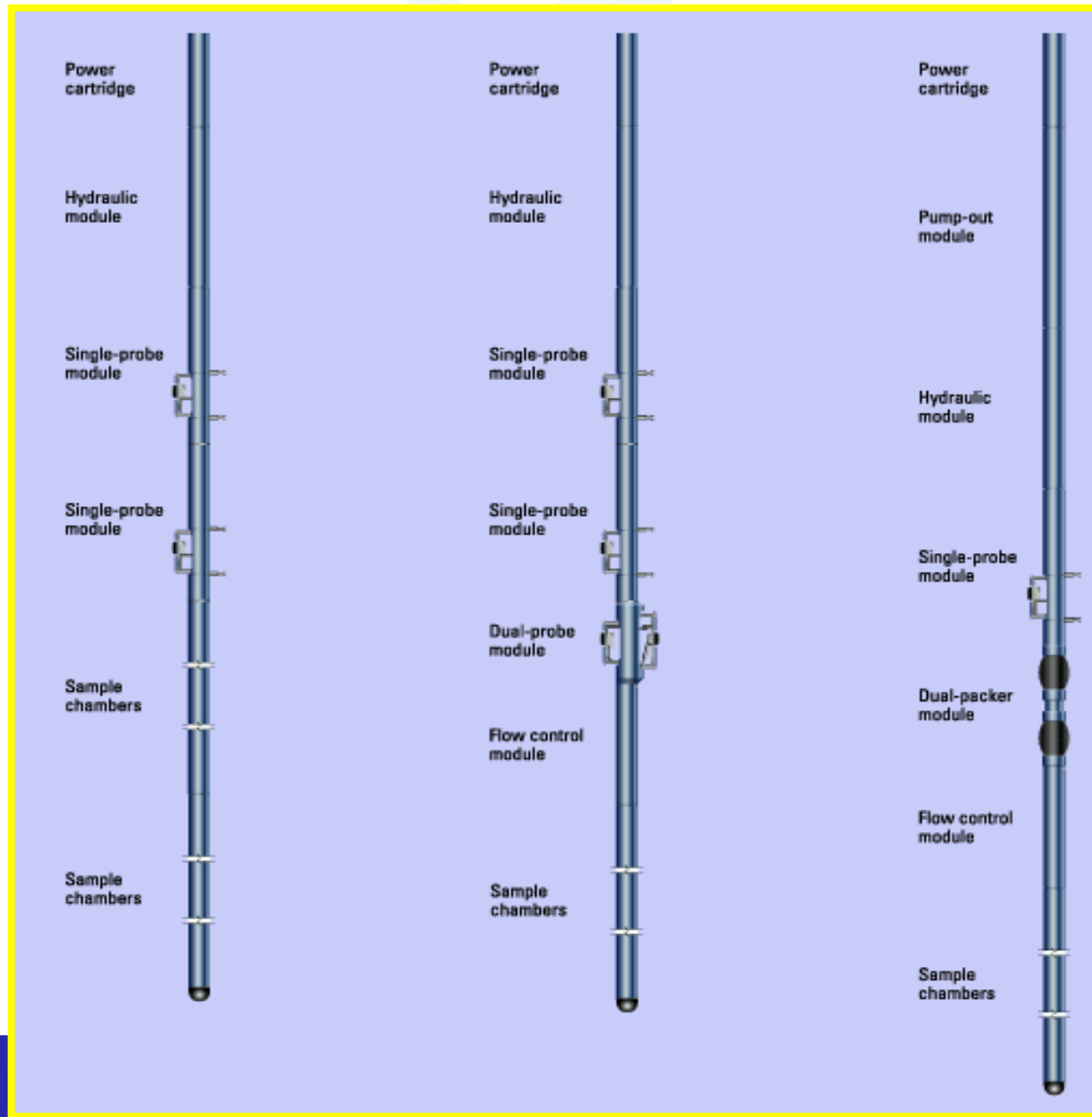
- Pressure measurements at desired depth;
- Pressure gradient and fluid density;
- Fluids contacts;
- Fluids mobility (proportional to permeability and viscosity);
- Fluids connectivity;

Sampling

- The samples of formation fluid can be analysed in laboratory;

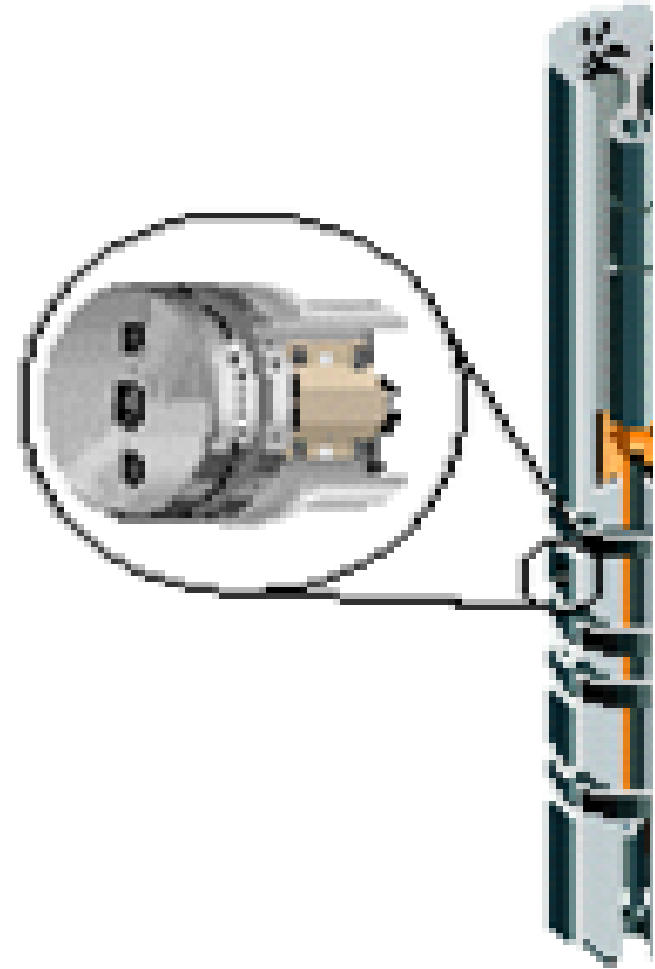


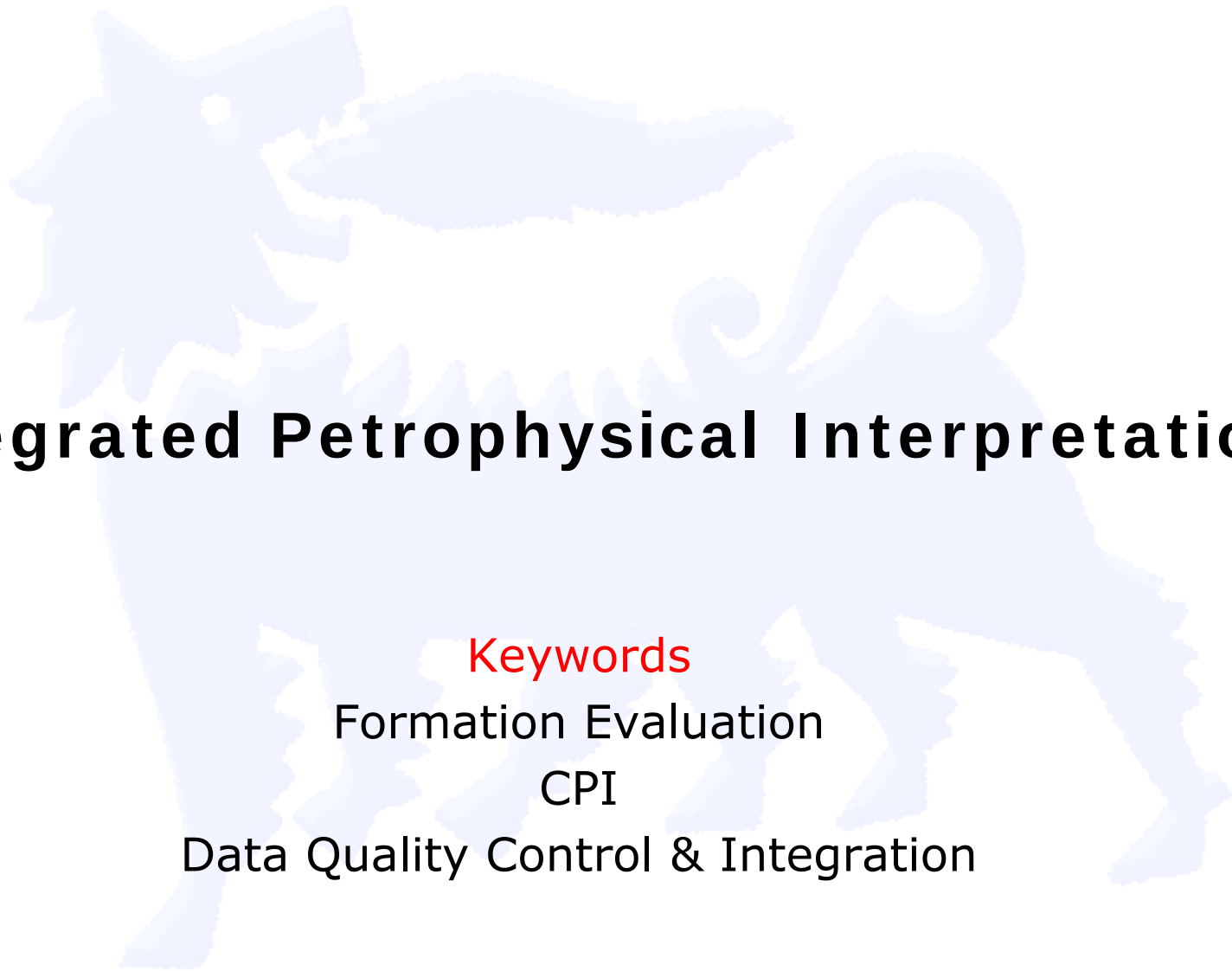
Wire Line Formation Testing: Modular Dynamic Tester (MDT)



Pressure measurements While Drilling (PWD)

A simple concept like measuring pressure downhole can profoundly impact a broad range of applications. Combined with other well parameters, these measurements are used to monitor borehole fluid conditions, which leads to early detection of problems such as stuck tools, annulus packoff, lost circulation and fluid influx. Monitoring annular pressure at the drilling bit also provides accurate formation stress measurements, making the process of drilling ahead safer and more exact.





Integrated Petrophysical Interpretation

Keywords

Formation Evaluation

CPI

Data Quality Control & Integration

Formation Evaluation Goal

- Objective of **Formation Evaluation** is to determine:
 - the dimension of the reservoir
 - **the quantity of hydrocarbon originally in place (HOIP)**
 - the productivity of the reservoir
- **Formation Evaluation** is the process of evaluating the petrophysical characteristics of a reservoir, making use of measurements and data from the well

Petrophysical Parameters

- The main petrophysical parameters that can be estimated from well logs are:
- Porosity Φ (total porosity, effective porosity)
- Permeability (**K**)
- Water Saturation (**S_w**, **S_{wi}**)
- The thickness of the productive layers can also be detected in order to evaluate *gross pay*, *net pay* and *net/gross*.

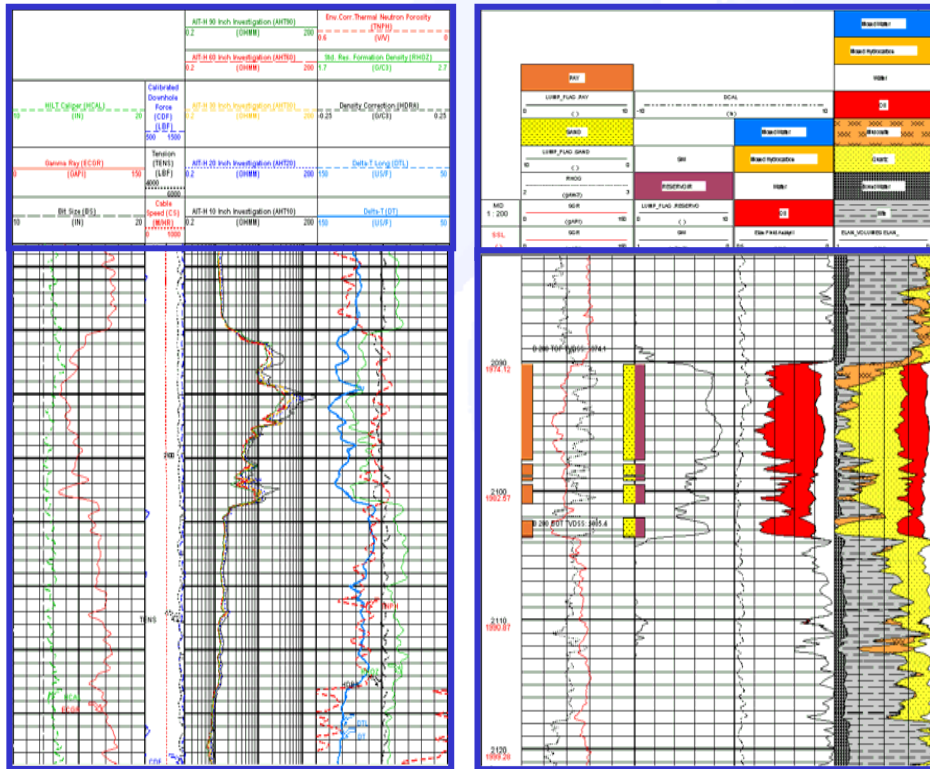
Computerized Petrophysical Interpretation (CPI)

- Different commercial software products are available on the market, both for PC and WS platforms. Some oil companies have developed proprietary programs.
- All these programs are based on one of these two different approaches:
 - The deterministic approach
 - The probabilistic approach

CPI : quality and robustness

- Input logs quality
- Interpretation model and parameters
- Interpretation tool available
- Balance between available measurements (number and quality) and the complexity of the interpretation problem
- Integration of all available data
- Experience and capability of the petrophysicist

CPI



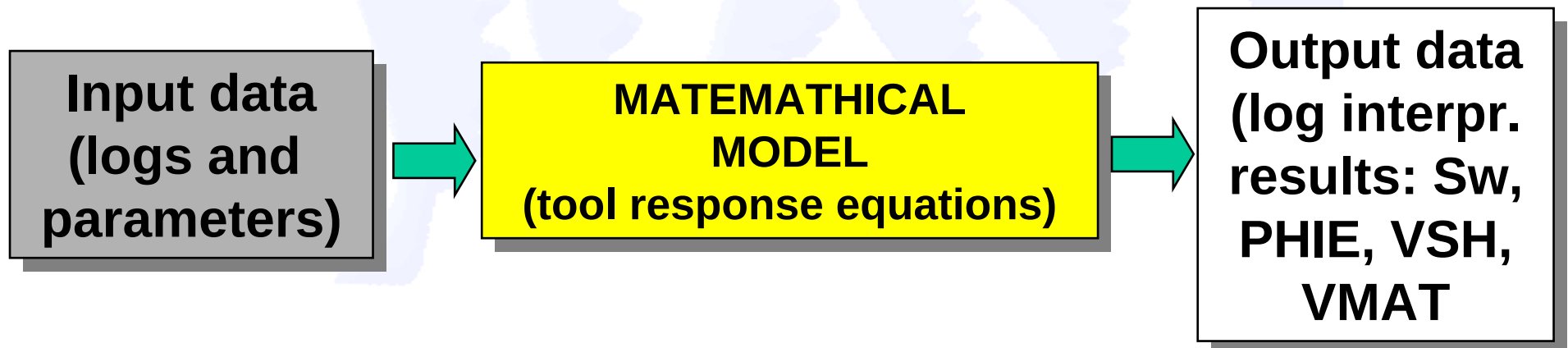
Quick look interpretation using ELAN:
An example from deep water Nigeria

In the industry **deterministic models** are widely used but we must know that these models are affected by several disadvantages

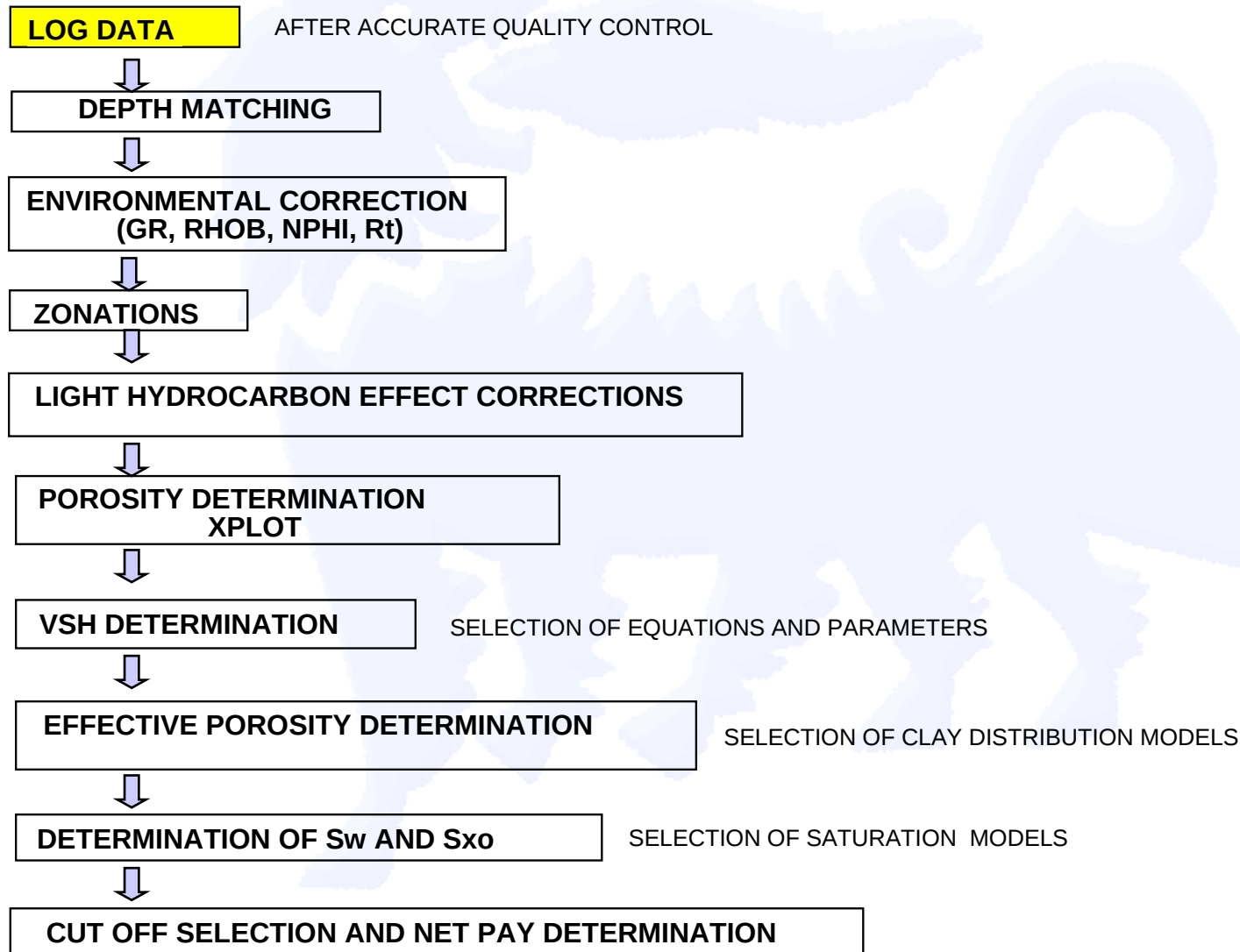
Probabilistic models are less easy to use but are intrinsically more objective and offer many advantages, thanks to their capability to process a wide selection of log data simultaneously

Quantitative Interpretation of Well Logs using Deterministic Models

The output petrophysical parameters are computed by a simple and direct solution of each tool response equation, at each depth point and following a logical sequence of operations (the operations used while manually interpreting the logs with charts and pocket calculators).



Quantitative Interpretation of Well Logs using Deterministic Models



Quantitative Interpretation of Well Logs using Deterministic Models

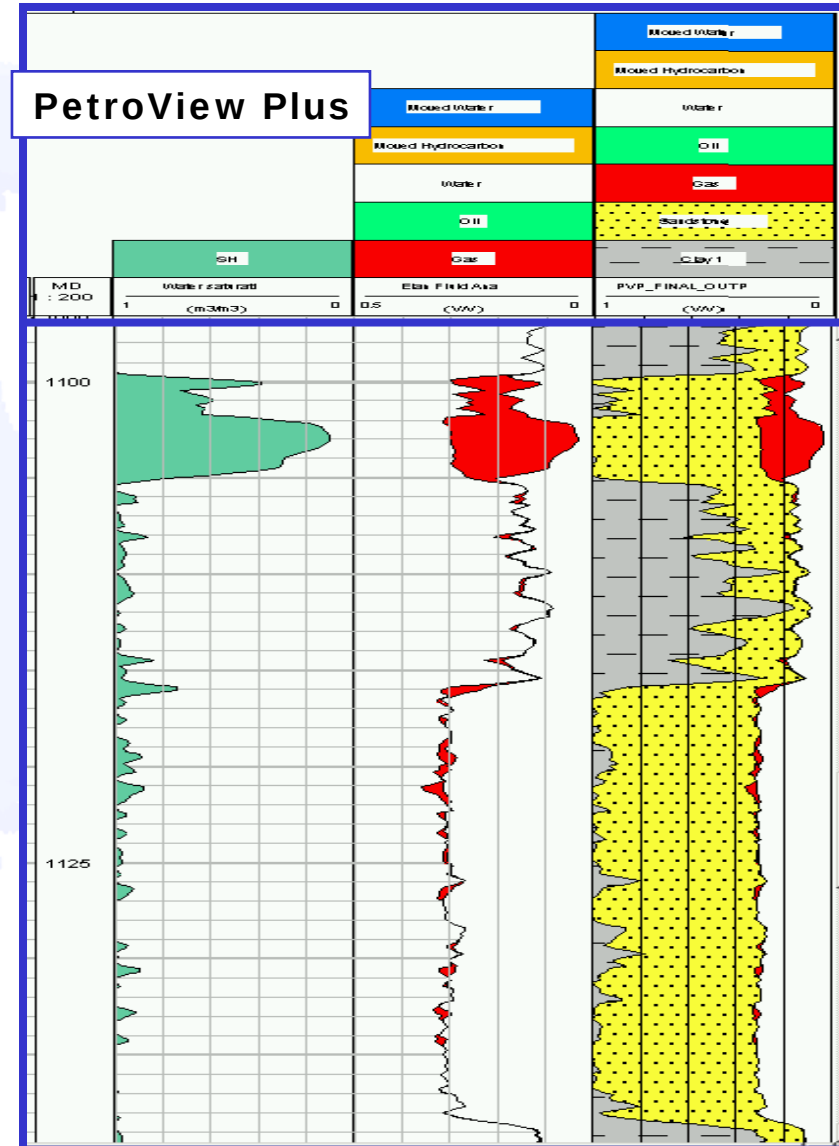
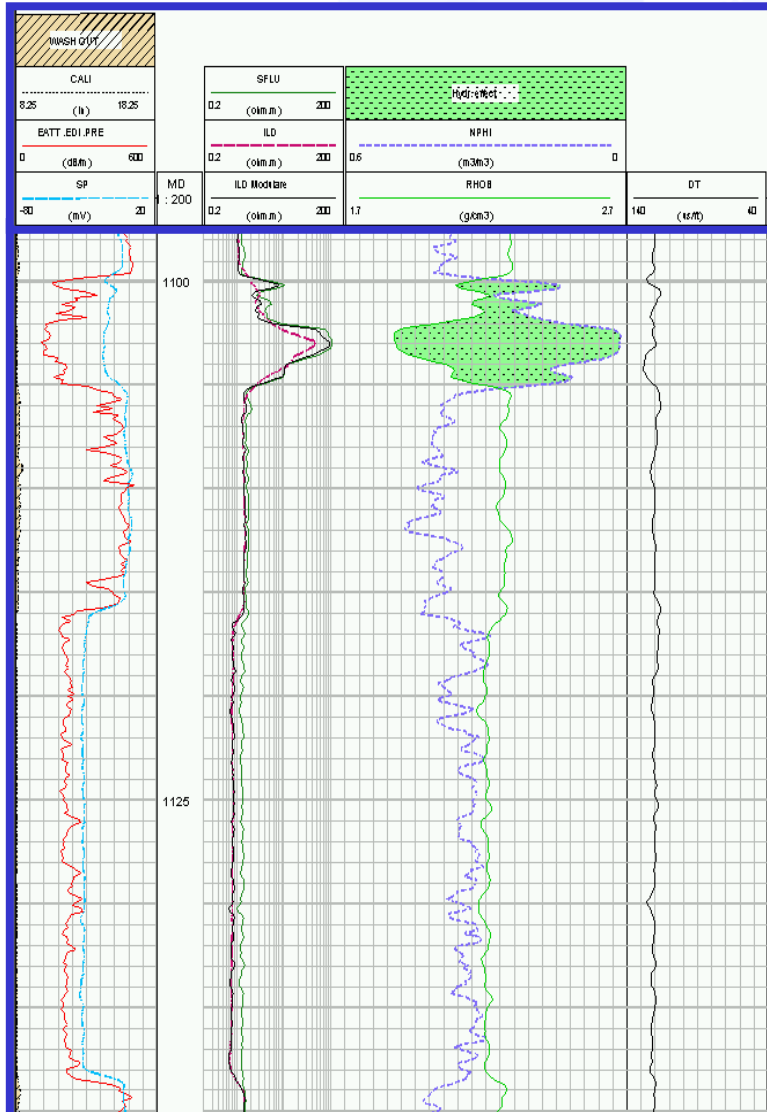
DISADVANTAGES

- porosity determination is limited to the use of simple one or two dimensional petrophysical correlations (Xplot Dens/Neut. or Sonic/Neutron);
- the input petrophysical parameters are selected by the analyst one by one and possibly modified by trial-and-error to obtain the “most satisfactory” solution (this solution is very subjective!).

ADVANTAGES

- the program follows, step by step, the typical sequence used for the manual interpretation; the approach is simple, easy to understand and to repeat several times.

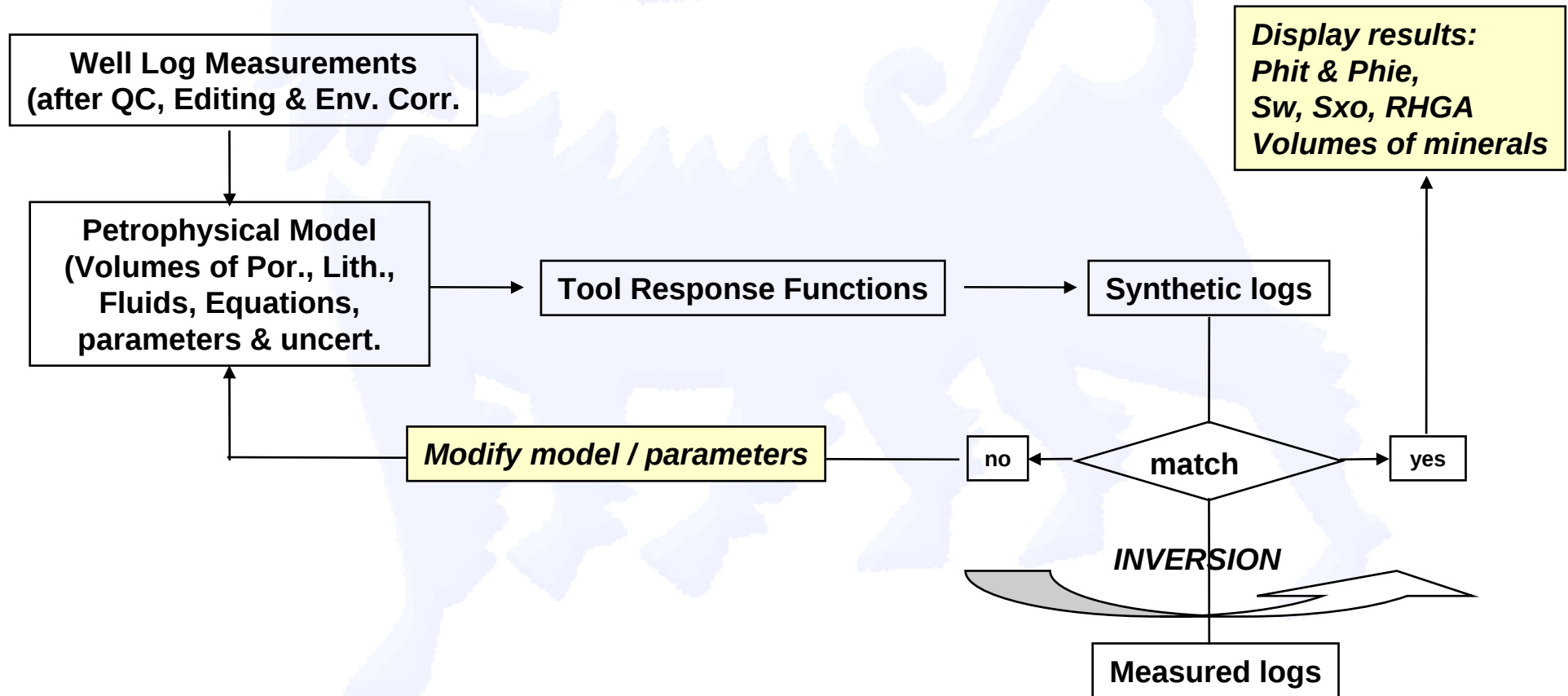
Quantitative Interpretation of Well Logs using Deterministic Models



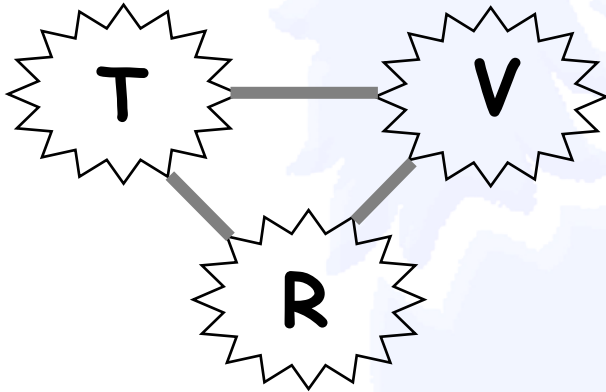
Quantitative Interpretation of Well Logs using Probabilistic Models

- search for global solutions allowing the optimized use of all the available log data;
- improved Q.C. of the results of the interpretation;
- solution of petrophysical problems in a n log dimensional space equation (*deterministic models suitable only for 2 dimension log problems*);
- use of probabilistic approach aimed at the definition of the most likely solutions (by inversion).

Quantitative Interpretation of Well Logs using Probabilistic Models



Quantitative Interpretation of Well Logs using Probabilistic Models



T = Well Log Measurements vector (input log)

R = Matrix of tool response functions

V = Vector of Volumes

FORWARD (Synthetic log computation)

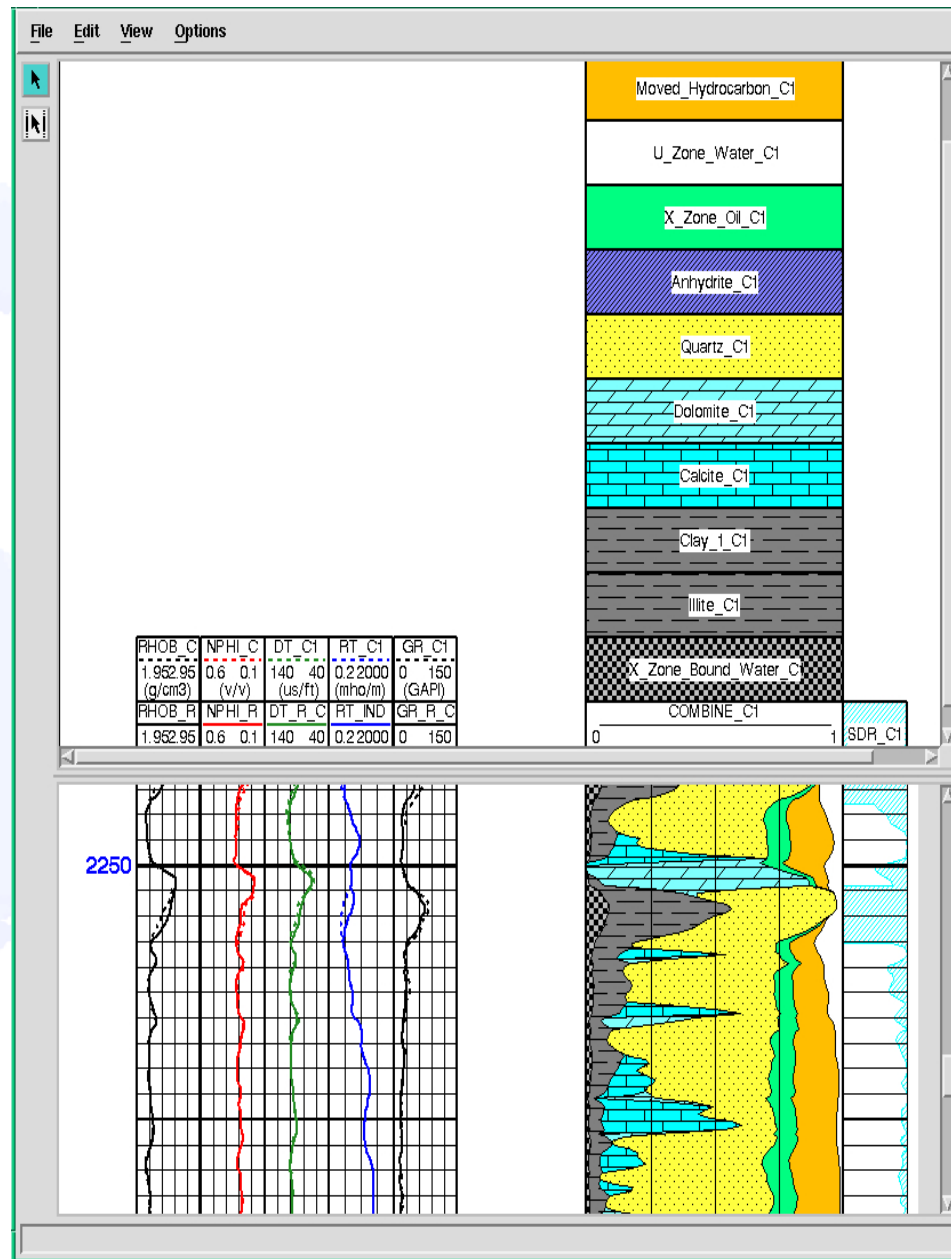
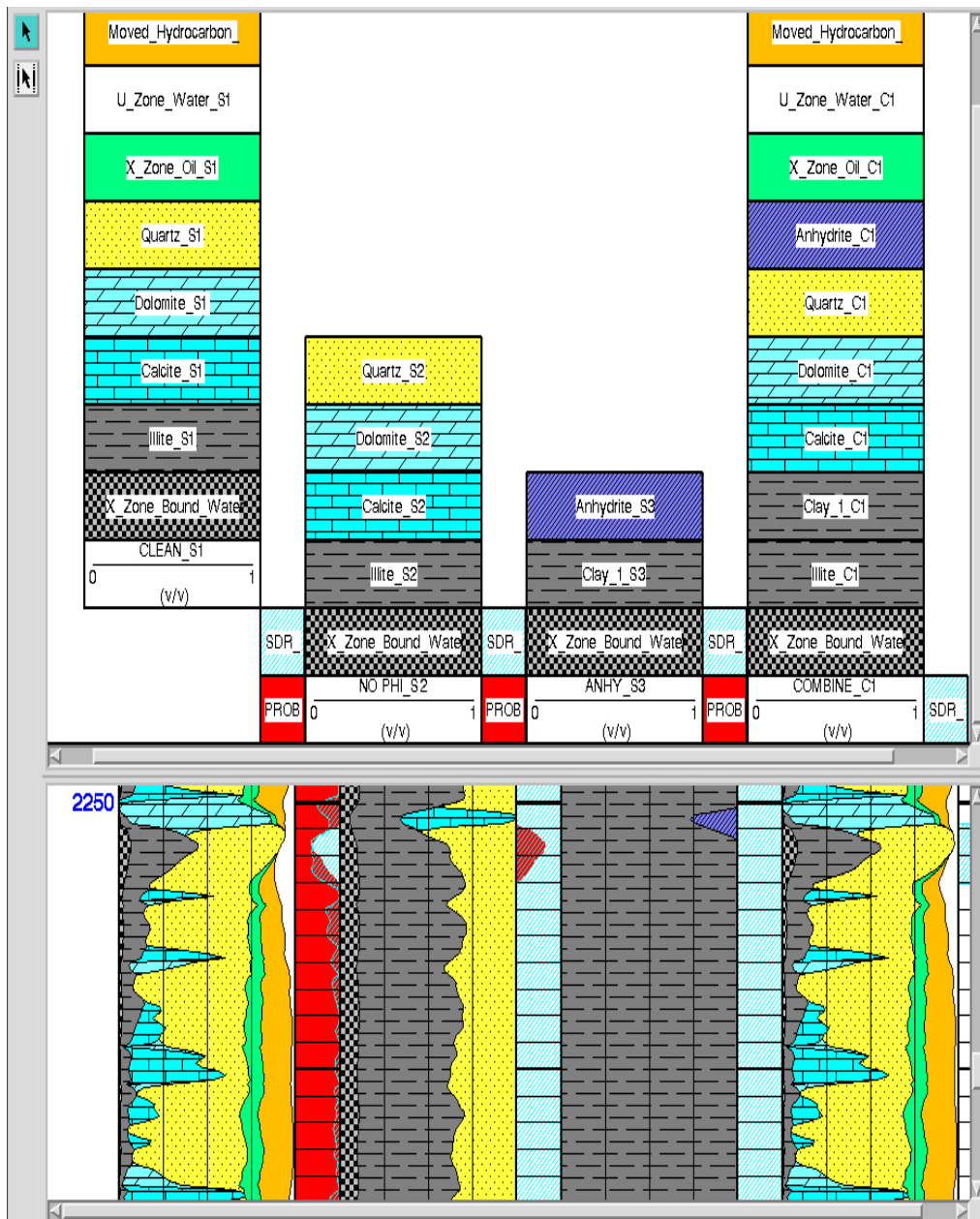
- R & V are used to compute T

INVERSION

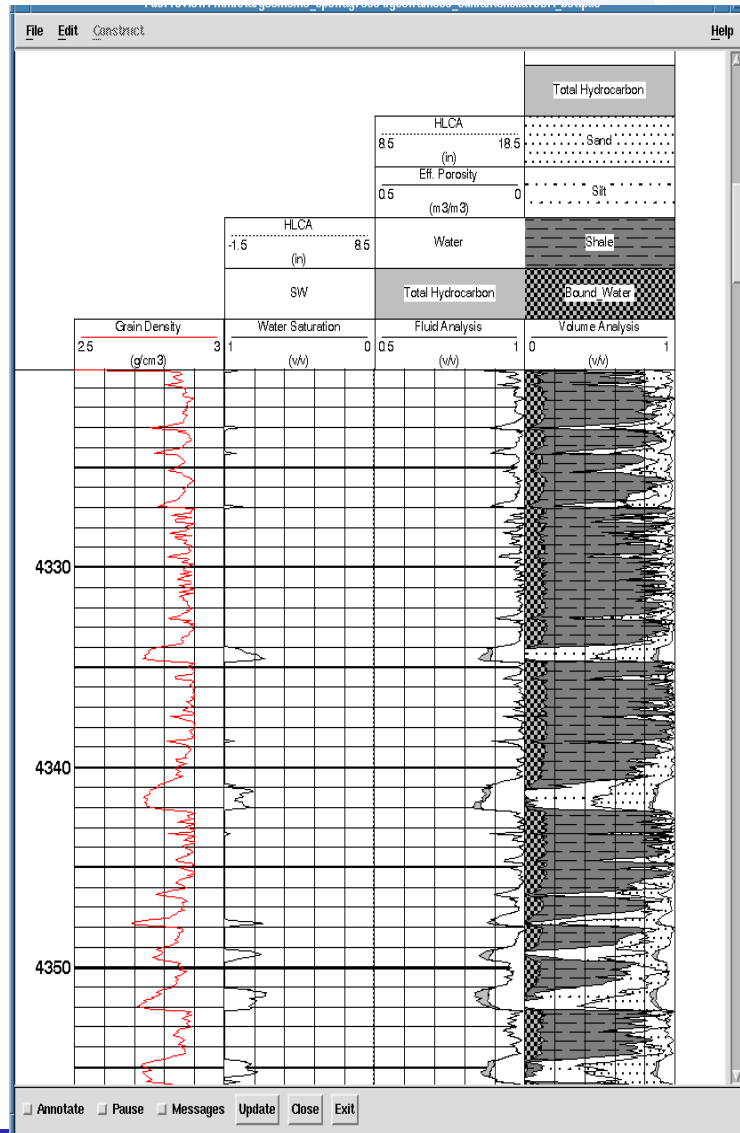
- T & R are used to compute V

CALIBRATION

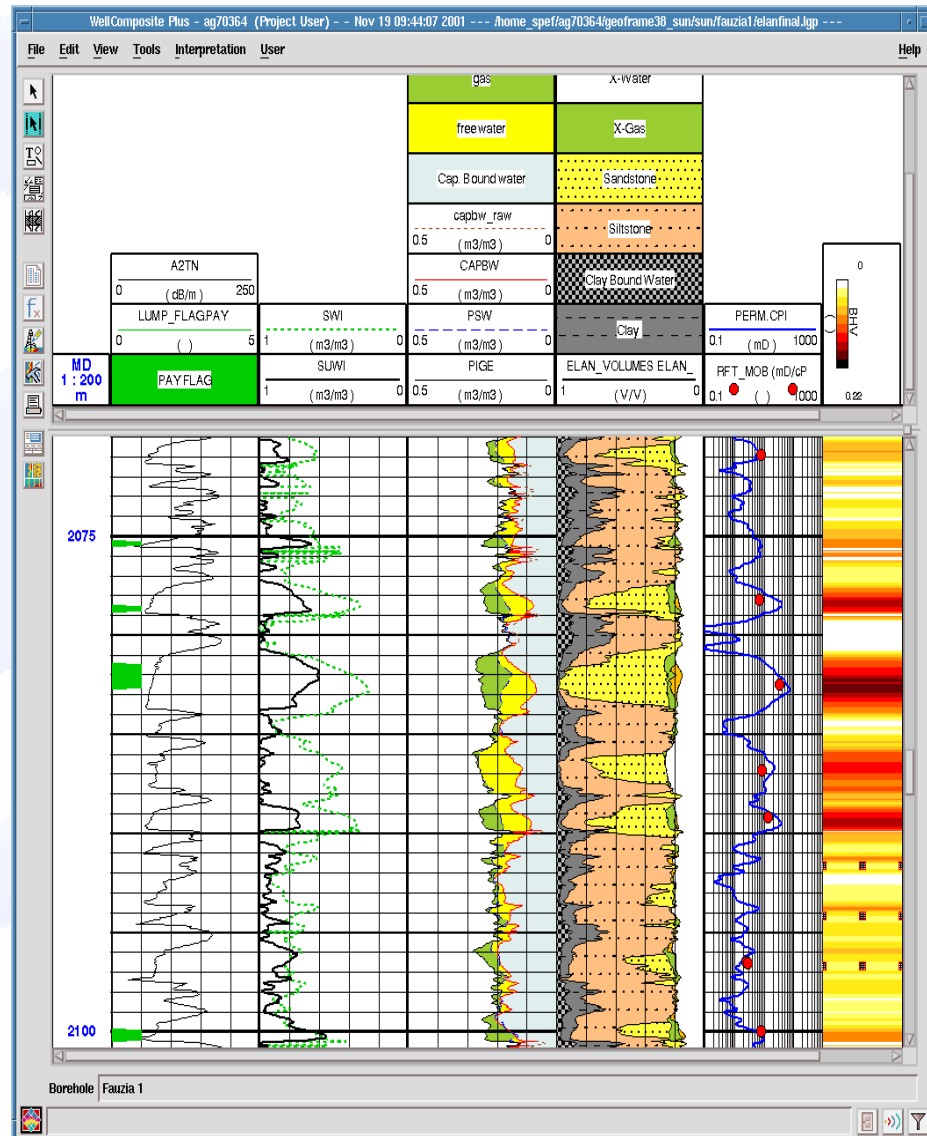
- T & V are used to compute R



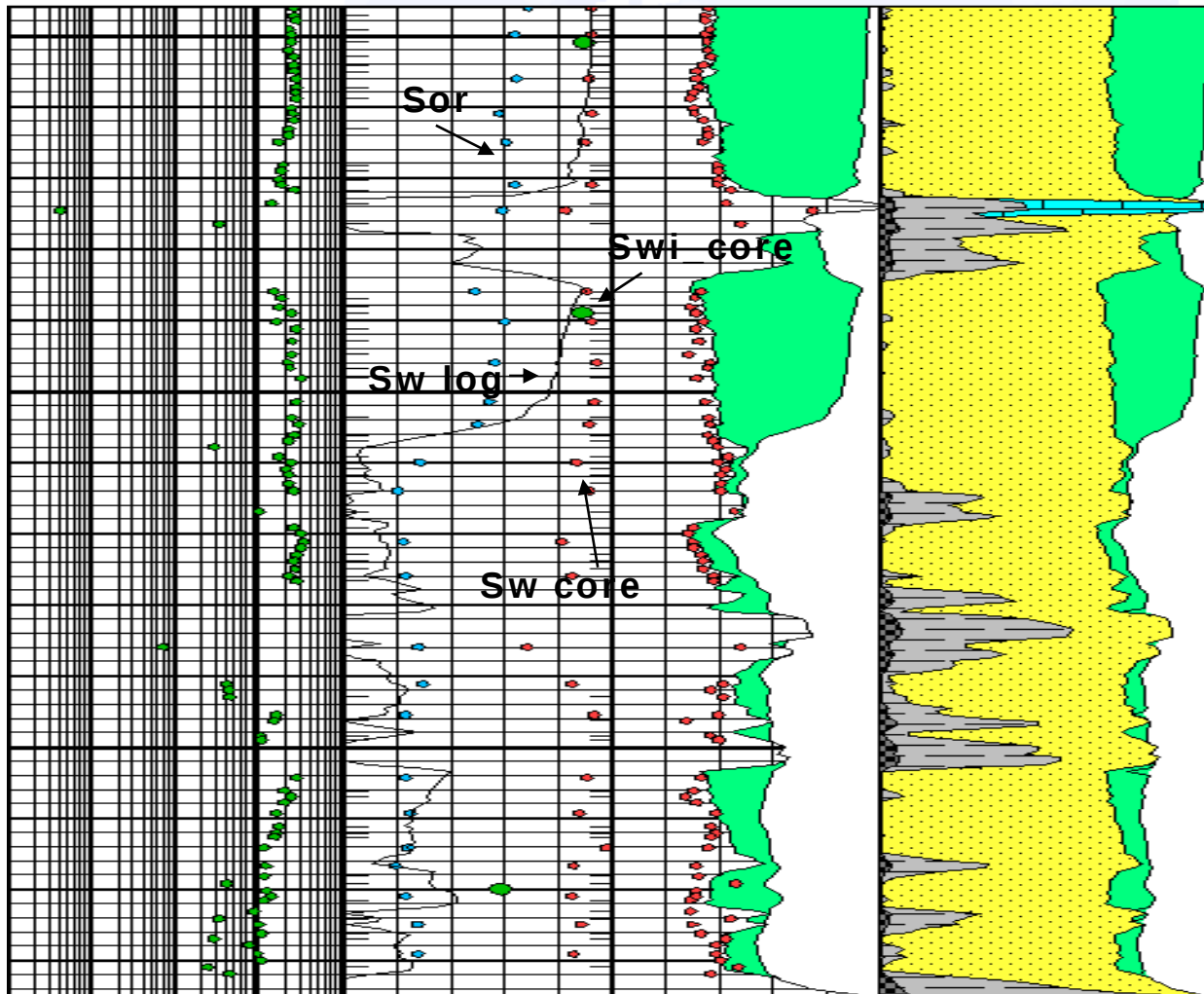
Traditional CPI



Elan Outputs + NMR



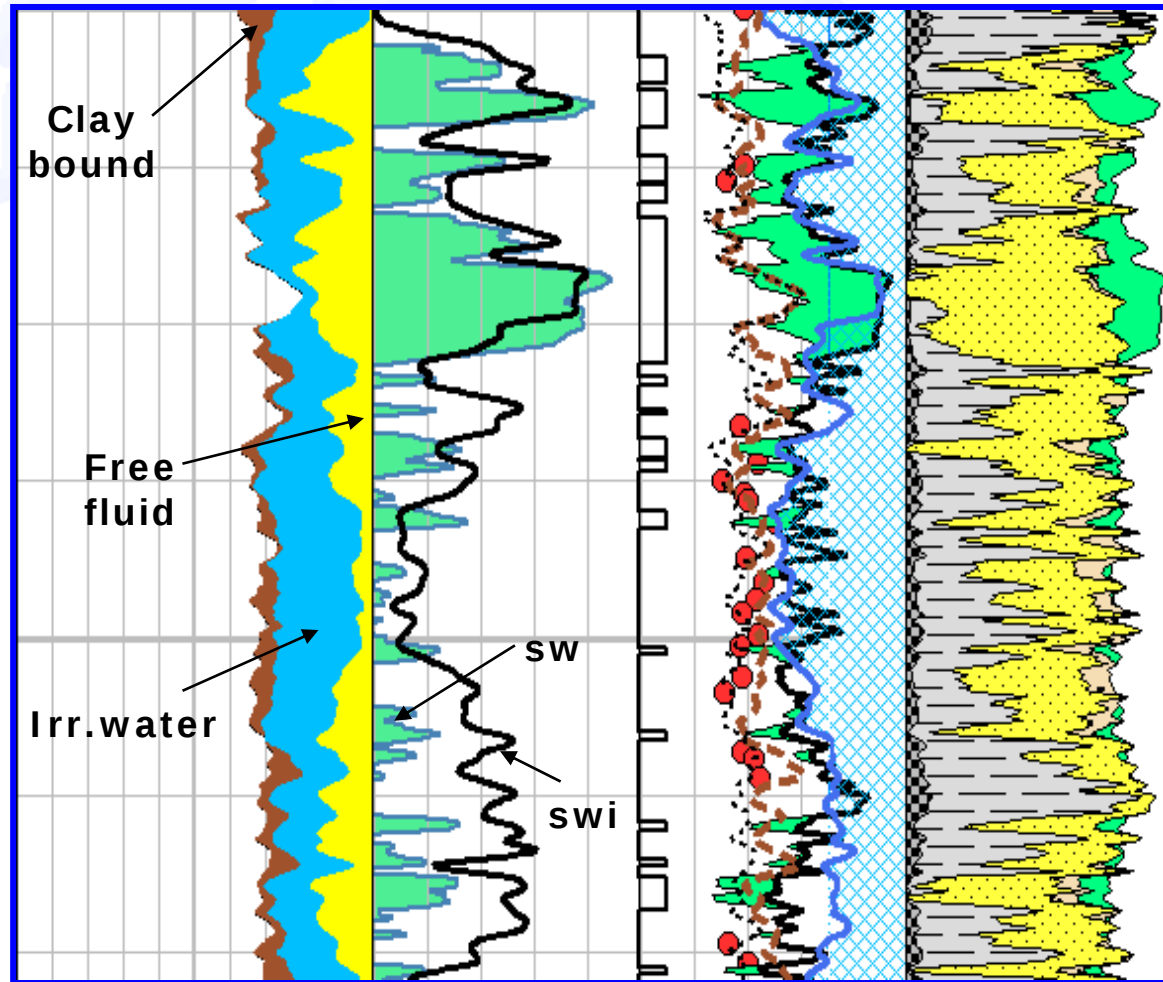
CPI – ELAN



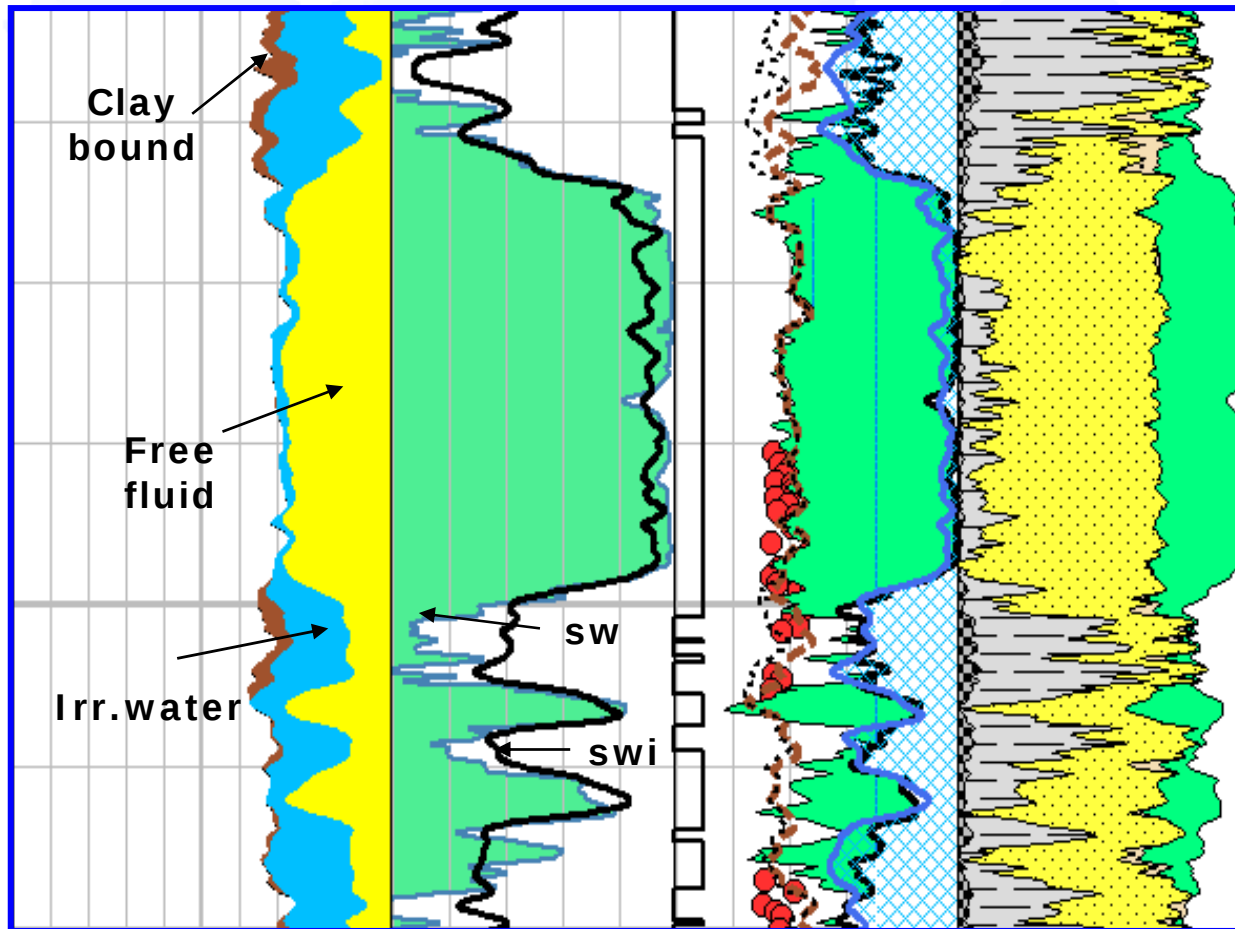
$S_w = S_{wi}$

Sw core lower than Sw log because has been lost (moveable fluid)

CPI - ELAN



CPI - ELAN





**Many Thanks, and
Have a Nice Day**